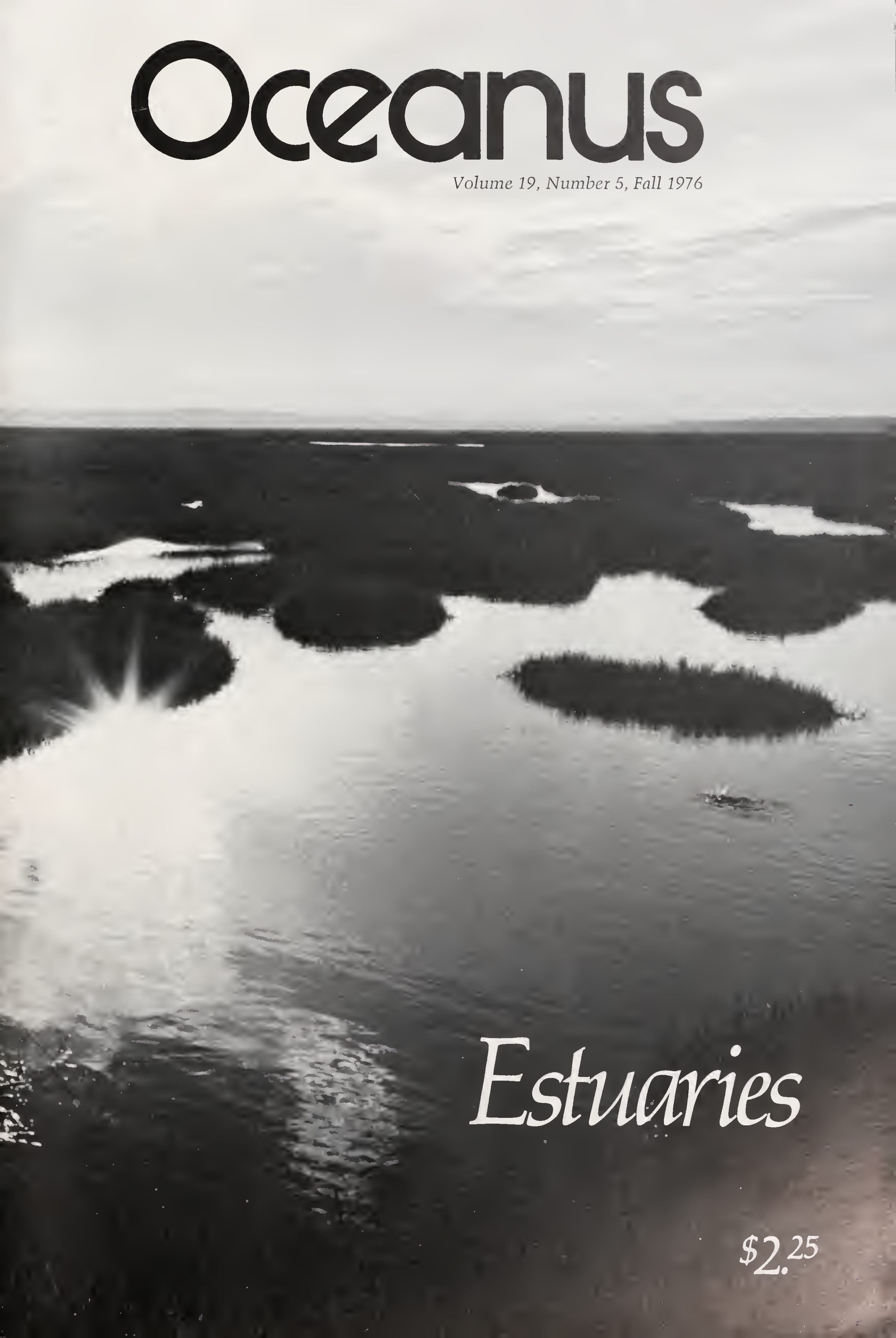
Oceanus

Volume 19, Number 5, Fall 1976



Estuaries

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Volume 19, Number 5, Fall 1976

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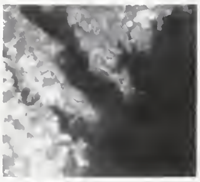

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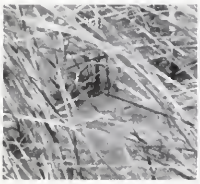

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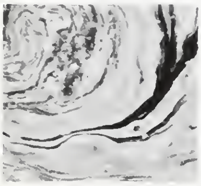

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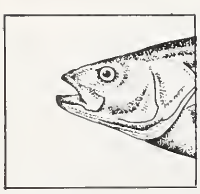

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Physical Oceanography of Estuaries

by Charles B. Officer

Estuaries are of immense societal importance, far beyond their relatively limited geographical extent. They are frequently areas of high fertility and large phytoplankton populations. The zooplankton of estuaries can be characterized in much the same terms as the phytoplankton; it is volumetrically abundant but often limited as to species composition. One of the more common and significant features of estuaries is the relatively large spring and summer zooplankton populations. This is a result of a high level of primary production. It also reflects the addition of numerous larvae of benthic invertebrates. It has been estimated that 60 to 80 percent of the commercial marine fisheries resources depend on estuaries for part or all of their life cycle. Man also concentrates much of his activities adjacent to the estuarine environment.

Apollo photograph of Chesapeake Bay, Norfolk, Hampton Roads, and Cape Charles area taken by 70mm Hasselblad camera aboard spacecraft that crew Thomas Stafford, Donald Slayton, and Vance Brand docked with Soyuz counterpart on July 17, 1975. (Courtesy NASA)

In the United States a third of the population lives and works close to estuaries. Of the 10 largest metropolitan areas in the world, 7 border estuarine areas (New York, Tokyo, London, Shanghai, Buenos Aires, Osaka, and Los Angeles). Of the 66 largest cities in the world, 39 are in coastal areas.

A knowledge and understanding of estuarine circulation and mixing is essential to the consideration of many of the problems that presently confront investigators looking at the chemical and biological aspects of water quality and ecology and the geological aspects of sediment transport and distribution. Our present understanding of the hydrodynamics of estuaries has evolved over the years through contributions from individuals with varying backgrounds in geophysics, physical oceanography, biology, chemistry, and civil engineering. Some of these contributions have come from purely scientific investigations, while others have been related to rather specific engineering problems. Recently, there has been an increased emphasis on understanding the circulation and mixing processes in estuaries, and this has been directly related to the existing and potential future pollution problems of estuaries.

Some indication of the increased interest in the geophysics of estuaries has been the recent occasion of two professional symposia on the subject. One, entitled *Geophysics, Estuaries, and the Environment,* was held at the American Association for the Advancement of Science meeting in February 1976 under the auspices of the Geophysics Research Board of the National Academy of Sciences. The other, entitled *Transport Processes in Estuarine Environments,* was held at the University of South Carolina under the auspices of their Institute for Coastal Research. The scientific papers from both symposia will be published in book form.

One of the general conclusions from both symposia was that we simply do not have an adequate scientific understanding of the physics, chemistry, geology, and biology of estuaries necessary for many of the environmental decisions that have to be made. We cannot predict with certainty the environmental effects of some changes: we do not even know the physical processes involved in others. Perhaps it was not that important to have this understanding in the past, and the faults of decisions made in good faith with the best of available knowledge could be tolerated. Perhaps this will not be the case for the future.

Estuarine Hydrodynamics

The term estuary has varying shades of meaning. From a standard English dictionary we have that an estuary is a wide mouth of a river where its current meets the sea and is influenced by the tides, or alternatively, that it is an inlet or arm of the sea. It is derived from the Latin *aestuarium,* which, in turn, is derived from the Latin *aestus.* As referred to the ocean the term *aestus* meant to the Romans the undulating motion of the sea, a swell or a surge, and later, as their explorations carried them beyond the Mediterranean, the ebb and flow of the sea, or the tide. The term *aestuarium* meant a place where the *aestus* was observable.

For geophysicists, physical oceanographers, and civil engineers, the definition of an estuary given some several years ago by D. W. Pritchard is usually followed. This is that an estuary is a semienclosed body of water having a free connection with the open sea and within which the seawater is measurably diluted with fresh water derived from land drainage. Traditionally the term estuary has been applied to the lower reaches of a river into which the seawater intrudes and mixes with fresh water draining seaward from the land. The term has been extended to include bays, inlets, gulfs, and sounds into which several rivers empty and in which the mixing of fresh and salt water occurs. We prefer this broader definition of an estuary.

As has been pointed out and elaborated by B. H. Ketchum, H. Stommel, and others, we are fortunate in having a natural tracer in estuaries. This is the fresh water flow into the estuary. A convenient measure of the fresh water fraction at any location can be given simply in terms of the observed salinity as referred to the normal ocean salinity of the coastal waters into which the estuary empties. From the observed vertical salinity distribution we can distinguish various estuarine conditions. We define a *well-mixed* condition as one in which there is essentially no variation in the salinity in a vertical column. We can also distinguish a stratified condition with a halocline between the upper and lower portions of the water column of nearly constant salinity. We define a *weakly, or partially, stratified* condition as one in which there is a change of salinity of only a few parts per thousand from surface to bottom, and a *strongly, or highly, stratified* condition as one in which there is a change in salinity of several parts per thousand from surface to bottom. We can also distinguish a condition in which there is an interface between two different water types. We define an *arrested salt wedge* as one in which there is a stable salt wedge underlying a strong, fresh water flow above, and a *fjord entrainment* type flow as one in which there is a relatively stagnant deep water mass overlain by a thin river runoff flow. It is important to appreciate that these are descriptive terms only and cannot, in general, be applied to an estuary as a whole; for any given estuary may show well-mixed or stratified conditions, for example, as a function of longitudinal distance along the estuary, season of the year, or even in some cases phase of the tidal cycle.

One of the better understood aspects of estuarine hydrodynamics is that of the longitudinal circulation and mixing characteristics for well-mixed and stratified estuaries as averaged over a tidal cycle. The driving forces for the circulation are the longitudinal surface slope force, acting in a downestuary direction, and the longitudinal density gradient force, related to the longitudinal salinity gradient, acting in an upestuary direction. These two driving forces are balanced by the internal and bottom frictional forces, and there may in some cases be an important contribution from a third driving force related to the wind stress at the surface. The surface slope force is constant as a function of depth, and the density gradient force increases essentially linearly as a function of depth. For the condition in which there is a small river runoff flow, which is common for many estuaries, the net effect is, then, that the surface slope force will be dominant in the upper portion of the water column, producing a net circulation flow downestuary, and that the density gradient force will be dominant in the lower portion of the water column, producing a net circulation flow upestuary. An example of this type of circulation is shown in Figure 1 for the Mersey Estuary. The longitudinal current velocity and salinity values are tidal averaged for a given station for four different measurement periods. The vertical coordinate is depth scaled to the total water depth.

Although this type of longitudinal density gradient flow is important, it is hardly an end in itself in understanding estuarine circulation. For larger estuaries, in particular, lateral effects, estuarine geometry, and atmospheric pressure and wind stress effects become important. In a paper presented at the South Carolina symposium, Pritchard discussed current records taken in Chesapeake Bay over an extended period of time of a year. He noted that, as averaged over a tidal cycle, one can observe times of reverse gradient flows in which the flow at the surface is upestuary and that near the bottom downestuary, times of storage flows in which the flow at all depths is either in an upestuary or downestuary direction, and times of three-layered flows in which the flow near the surface and the bottom are in one direction and that at mid-depth in the other direction in addition to times of the normal density gradient flow. Certainly one conclusion from these observations is that we have much to learn.

The previous two paragraphs have concerned the mean motion as averaged over a tidal cycle. The tidal motions, themselves, are of great importance in most well-mixed and stratified estuaries for the mixing and ultimate longitudinal dispersion of potential pollutants and in the determination of bottom and internal frictional effects. In terms of a simplified longitudinal dispersion coefficient, there are two contributing effects, one from the tidal mixing itself and the other from the net circulation, or velocity shear, effect of the mean motion. For estuaries in which

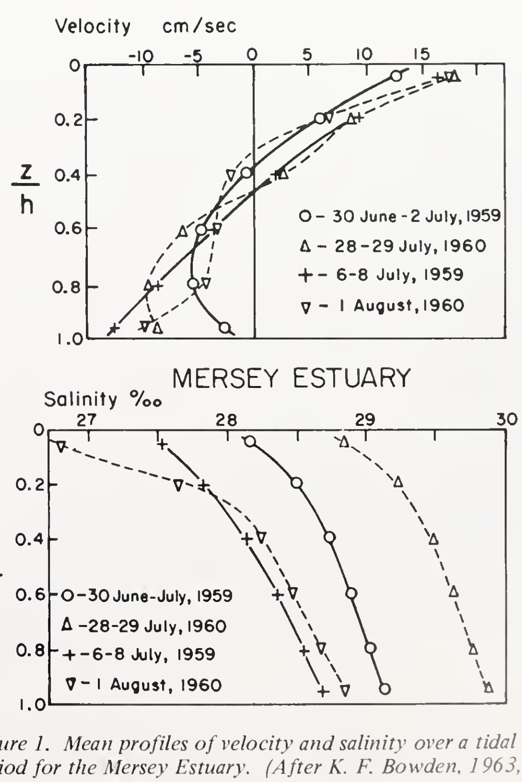

Figure 1. Mean profiles of velocity and salinity over a tidal period for the Mersey Estuary. (After K. F. Bowden, 1963, Int. J. Air and Water Pollut., *7:343-46, Fig. 2.)*

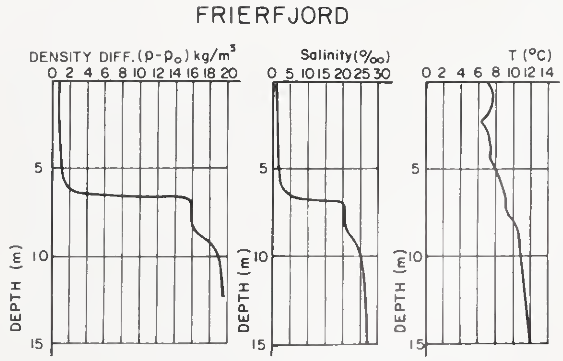

Figure 2. Observed stratification, Frierfjord, October 26, 1966. (After T. Carstens, 1970, American Society of Civil Engineers, J. Waterways and Harbor Div., *vol. 96, WW1, pp. 97-104, Fig. 1.)*

there is substantial tidal motion, the tidal mixing contribution will usually be dominant.

For conditions in which an interface exists between two different water types, simple two-layered hydraulic theory can describe several of the basic observables. Beyond this and in consideration of interfacial stability and entrainment and mixing across the interface, or steep gradient, the physical understanding and theoretical description become considerably more complex. An example of summer conditions in a Norwegian fjord is shown in Figure 2. The interface is quite sharp, showing a change in salinity of several parts per thousand over a vertical distance of a fraction of a meter.

One possible method of investigating estuarine interfaces is that shown in Figure 3. This is a high-frequency acoustic reflection record of the salt wedge interface in the Ishikari River; the type of record is much the same as a conventional echo sounder record of the bottom. Some question can be raised as to whether the acoustic reflection is returned from the impedance contrast across the fresh to salt water interface or from detritus or bubbles accumulated on the interface. In either case it would appear to be an interesting technique that might be used for investigating the dynamics of estuarine interfaces and hydrodynamic flow conditions.

Applications

Estuarine hydrodynamics finds application in the description of water quality parameters such as biochemical oxygen demand and dissolved oxygen, nutrient cycle relations, and coliform bacteria distribution; in the description of the geological parameters of suspended sediment and particulate matter distribution and transport and bottom

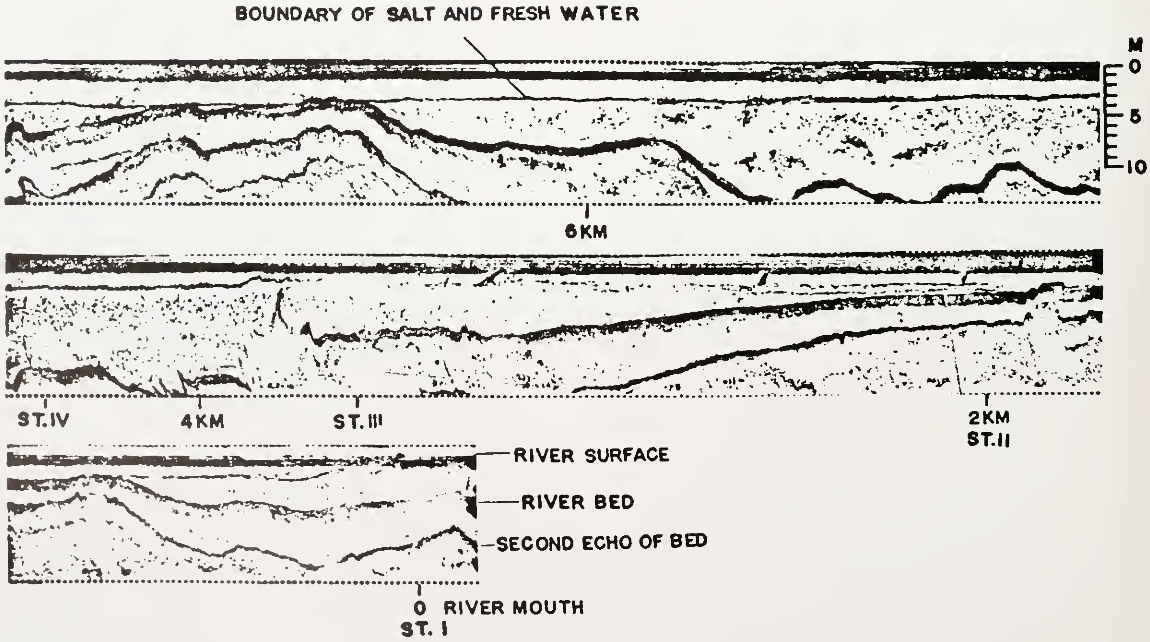

Figure 3. A longitudinal profile of a salt wedge in the mouth of the Ishikari River, July 22, 1964. (After H. Eukushima, M. Kashiwamura, and I. Yakuwa, 1966, American Society of Civil Engineers, Proceedings of the Tenth Conference on Coastal Engineering, pp. 1435-47, Fig. 10.)

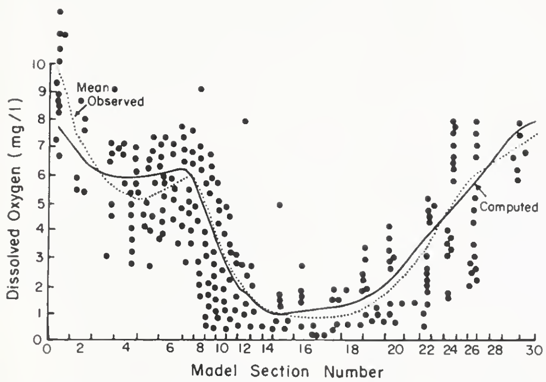

Figure 4. Computed and observed dissolved oxygen profiles for the Delaware Estuary, June-August, 1964. Dots represent individual grab samples. (After R. V. Thomann, 1972, Systems analysis and water quality management, *McGraw-Hill, New York, Fig. 7-7.)*

sediment transport; and in the description of the biological parameters of phytoplankton, zooplankton, and fish eggs and larvae distributions and blooms. For the first, the substances are miscible and the hydrodynamic equations can be applied directly with appropriate chemical and biological reaction and interaction effects included. For the second, the substances are not miscible with the estuarine waters; other physical processes become involved, which complicate a quantitative description. For the third, essentially only a qualitative, or statistical, description can be given.

One of the more successful applications has been in the description of dissolved oxygen and coliform bacteria distributions and, to a lesser extent, nitrogen cycle relations for various estuaries. These descriptions, for the most part, have been made for cross-sectional and tidal-averaged conditions under steady state. Coupled linear differential equations are used. Each equation is in the form of a one-dimensional, longitudinal equation with a net advection term, a dispersion term, including both tidal mixing and net circulation effects, and various reaction terms for the decay or build-up of the quantity considered and its feedforward and feedback contributions. Solutions are usually given through finite difference numerical calculations, with a computer, that permit the important inclusions of changes in geometry, coefficient values, and pollutant and fresh water source contributions along the estuary. Sometimes the dispersion, reaeration, and reaction coefficients are determined from separate experiments; sometimes they are determined by adjustment to give a best fit of the model to the field observations. An example of a comparison of the numerical model calculations and the field observations for dissolved oxygen along an extended length of 135 kilometers for the Delaware Estuary is shown in Figure 4. Although on the average the comparison is quite good, this figure also raises indirectly questions as to the relative importance of tidal, transient, vertical, and lateral effects in describing the scatter in the field observations.

Let us continue, now, with a consideration of the application of estuarine hydrodynamics to geology. One of the more important indices as to bottom sediment transport is the direction of the tidal-averaged bottom current. For the middle to lower reaches of a well-mixed or stratified estuary, longitudinal density gradient flow will usually be dominant, and the net bottom current will be in an upestuary direction. For the upper reaches of an estuary and its associated tributary river, the longitudinal salinity gradient effect will be negligible, and the flow will usually be riverine in character and downestuary at all depths. We would then expect that the region of sediment accumulation would be at the null zone between these two flow conditions. In the gross this is indeed the case. An example for the Savannah River is shown in Figure 5. The flow at the surface is predominantly downestuary. That at the bottom is predominantly downestuary from the upper end of the harbor to about station 130, and predominantly upestuary from this station to the harbor entrance. The region of shoaling is in the vicinity of zero net bottom motion.

Another related geological aspect is that of the suspended particulate matter distribution in an estuary. One of the more interesting aspects of such distributions is the turbidity maximum, which exists in the upper reaches of a number of estuaries. The turbidity maximum is related, at least in part, to a local resuspension of bottom sediments by tidal

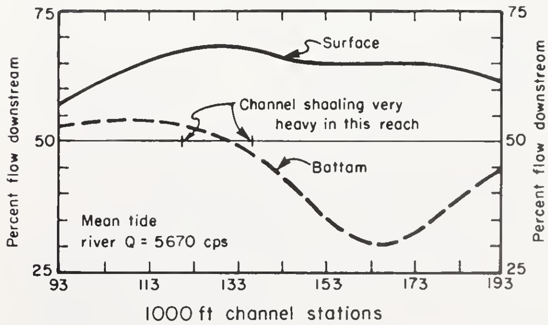

Figure 5. Relation between normal surface and bottom flow in Savannah Harbor. (After H. B. Simmons, 1966, Estuary and coastline hydrodynamics, *McGraw-Hill, New York, pp. 673-90, Fig. 16.9.)*

action in the accumulation zone. An example for the northern reach of San Francisco Bay is shown in Figure 6. The magnitude of this turbidity maximum increases with the increased, winter suspended particle input; and its position varies in response to the tributary river discharge.

A third hydrodynamically related geologic effect is the dense static suspensions of fine cohesive sediments that sometimes occur in estuaries and form a distinct layer above the normal bottom. These suspensions are variously referred to as fluid mud, fluff, and flocculent layers; and the particle concentrations are quite high—of the order of 100,000 milligrams per liter or more with corresponding densities of 1.1-1.4 grams per milliliter. They are somewhat ephemeral in character. They move with the bottom current, and they are sometimes present or absent depending on the phase of the tidal cycle or the neap to spring tidal variations. Where observed, they have been found

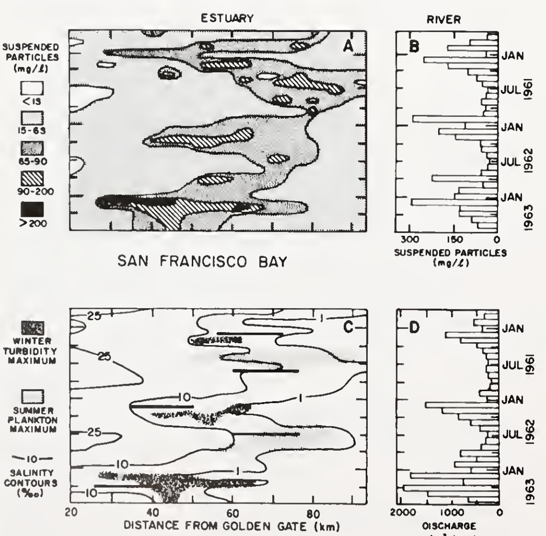

Figure 6. Seasonal distribution of properties in the northern reach of San Francisco Bay, 1961-63: (A) Suspended particle concentration in the estuary; (B) suspended particle concentration in Sacramento River; (C) salinity at 1 meter depth in the estuary compared with location of suspended particle and plankton maxima and approximate location of nontidal current null zone, solid black lines; (D) combined discharge from Sacramento and San Joaquin rivers. (After D. H. Peterson, T. J. Conomos, W. W. Broenkow, and E. P. Scrivani, 1975, in Estuarine Research, *ed. L. E. Cronin, vol. I, Academic Press, New York, pp. 153-87, Fig. 9.)*

to be quite high in heavy metal content and are apparently largely anerobic, both phenomena being of potential environmental significance. These layers are readily distinguishable on a conventional echo sounder record, and an example for the Severn Estuary is shown in Figure 7.

With regard to the interrelations and dependence of estuarine biota on hydrodynamic effects, we enter a more complex arena. Much of the scientific investigation in the past in estuaries has been directly related to the biota. This will probably be true for the future, but perhaps with more emphasis on physical, chemical, and geological interrelated biological effects rather than discipline-oriented biological descriptions. Here the discussion is limited to two examples where hydrodynamics appears to play an important role in the description of the biota.

The null zone, which occurs in the upper reaches of some estuaries between the riverine and density gradient type flow conditions, is also the region of maximum residence time for the passage of a water particle from its tributary river to the ocean. It becomes an important region for phenomena that are time-dependent for their generation. It can be argued, then, that the null zone will permit the highest *in situ* summer phytoplankton growth, or bloom, through reproduction. An example that this dependence does exist is shown in Panel C of Figure 6 for San Francisco Bay. Here the summer plankton maximum corresponds well with the location of the null zone, as does the winter turbidity maximum.

A few years ago E. L. Bousfield, in a paper in the *Journal of the Fisheries Research Board of Canada* (12:342-61), described the general oceanography and biota of the Miramichi Estuary. A feature of particular interest is the effect of the estuary net circulation, or density gradient controlled, flow on the distribution of the larval stages of a brackish water barnacle *Balanus improvisus* during its 18-day planktonic life period. The first three nauplius stages, found mainly in the upper portion of the water column, are transported successively seaward. The fourth and fifth stages, found near mid-depths, are concentrated near the mouth of the estuary. And the sixth-stage nauplius and the cyprid, found mainly in the lower portion of the water column, are carried progressively landward toward the head of the estuary. It would

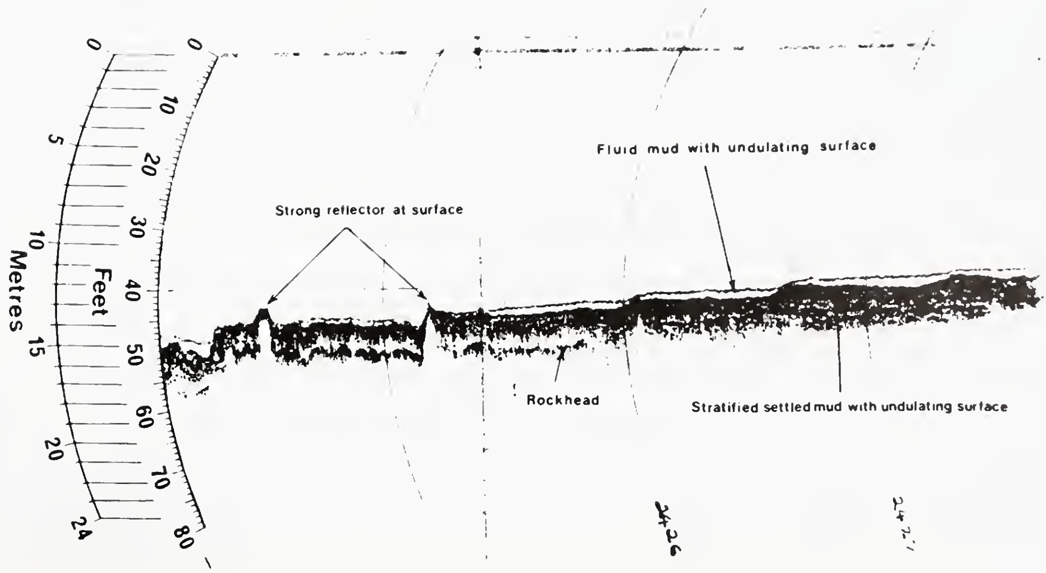

Figure 7. A 30-kilohertz echo sounder record showing fluid mud and settled mud in the Severn Estuary. (After R. Kirby and W. R. Parker, 1974, Dock and Harbour Authority, *54:423-24, Fig. 1.)*

appear then that, at least in this case, the ecology of such biota is dependent not only on the environment of their adult habitat but also on the environment of the estuary as a whole.

Charles B. Officer is an adjunct professor of earth sciences at Dartmouth College and a partner in Marine Environmental Services. He also is a guest investigator at the Woods Hole Oceanographic Institution.

Suggested Readings

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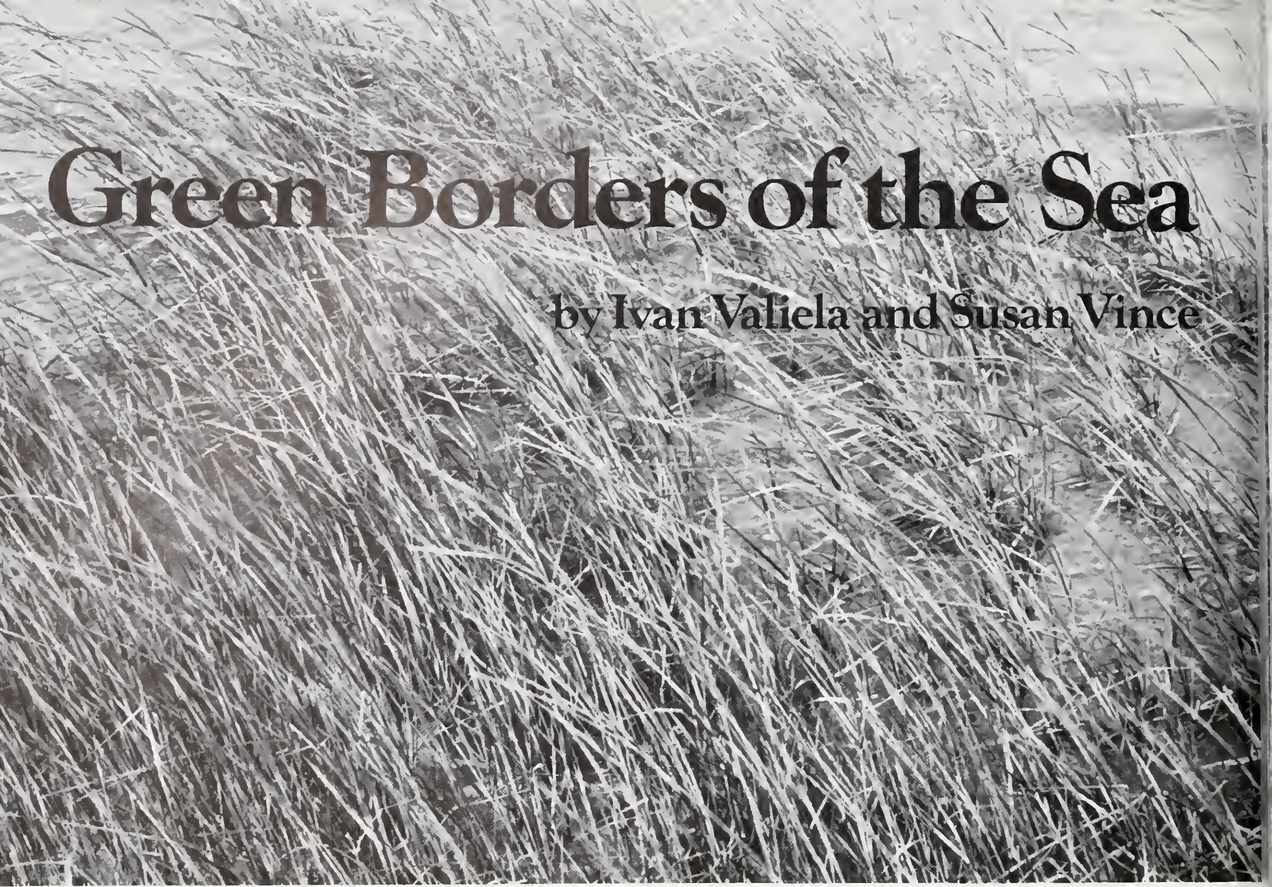
Green Borders of the Sea

by Ivan Valiela and Susan Vince



Spartina alterniflora *or typical salt marsh cord grass found from Nova Scotia to Texas. (Paul J. Godfrey)*

The margins of the world's oceans and estuaries are largely bordered by a narrow green ribbon of vegetation. For geographical and economic reasons, these coastal strips have been severely stressed and altered over the centuries. The variety of benefits provided by wetlands has only recently become well documented. Unless society has a better understanding of the losses incurred in destroying wetlands, this historical pattern will continue.

Wetlands are of two types: salt marshes or mangrove swamps (Figure 1). The plants found in salt marshes are mainly grasses, while mangrove swamps are dominated by various species of mangrove trees. In temperate latitudes, *Spartina* grasses are the most common, while most mangrove vegetation consists of members of the genera *Rhizophora, Avicennia,* and others. Only a few types of plants have evolved to live in this border between sea and land. Marsh and mangrove plants grow in oxygen-poor mud and peat intermittently submerged by seawater. The plants have a variety of adaptations to solve these environmental problems, such as specialized glands to excrete salt. Marsh grasses have a system of conduits carrying air to the part of the plant growing underground. Mangroves have air-containing vessels in their roots as well as aerial prop roots, or pneumatophores, to accomplish the same purpose.

Marshes and mangroves are distributed all over the world and either are associated with estuaries or are found behind island bars that provide protection from the open sea (Figure 2). No one has satisfactorily explained the striking degree to which the boundary between marshes and mangroves parallels latitude on all continents. Mangroves cover much of the coasts between 30°N and 30°S, and marshes take over north and south of these latitudes (Figure 1). In a number of places—southern Brazil, Florida, northern New Zealand—mixtures of both types of vegetation appear. Where mangroves and grasses grow together, mangroves can outgrow and shade grasses. In the absence of mangroves, well-developed marshes would be found nearer the Equator. *Spartina* grasses grow on Brazilian coasts as well as in temperate North America, but the Brazilian stands occur where the mud has not yet been colonized by mangroves. The explanation for the sharp boundary may require only an accounting of why mangroves cannot grow beyond the tropics. There is some speculation that mangrove seedlings cannot survive freezing temperatures. No experimental evidence is available, however, and in some localities where mangroves are found, freezing does occur.

Pressure on the Wetlands

Concern with mosquito-borne diseases has historically colored attitudes toward coastal wetlands. Sixteenth-century Spaniards made a point of founding Buenos Aires ("good airs") on a site where winds blew the presumed "bad air" (*mala aria* is the Italian origin of our word for the mosquito-borne fever) of coastal marshes seaward. As it turned out, the place was not well situated, since neither the local tribes nor the mosquitos were kind to the settlers.

Health hazards are one thing, economics quite another. Marshes and mangroves often flourish where human settlements are likely to prosper—protected sites at the junctures of river and sea transportation routes. The result has been widespread filling and the disappearance of wetlands. The expansion of Boston over the marshy estuary of the Charles River and Boston Harbor is a good example (Figure 3). Another is the development of Venice since A.D. 600 over the marshy lagoons and sand bars at the head of the Adriatic. This took place despite the continued policy of the Venetian administration against altering the lagoon. In the mid-thirteenth century, a dam was built across the low-lying, marshy Amstel River, starting the long struggle between settlement and tidal water that has produced present-day Amsterdam.

Another reason for the reduction of coastal wetlands is that these areas can be used for agricultural and industrial purposes because of the fertile soils and normally low land prices. In Java, Sumatra, the Philippines, and Taiwan, mangroves have been cleared to produce systems of carefully managed tidal ponds fringed with mangrove levees. Fish and prawn are cultured in such ponds, and production is among the highest recorded. More damaging practices have been used in Sri Lanka and Mozambique, where reclaimed swamps are now coconut groves. In Thailand and Mozambique erstwhile mangrove areas have become shallow

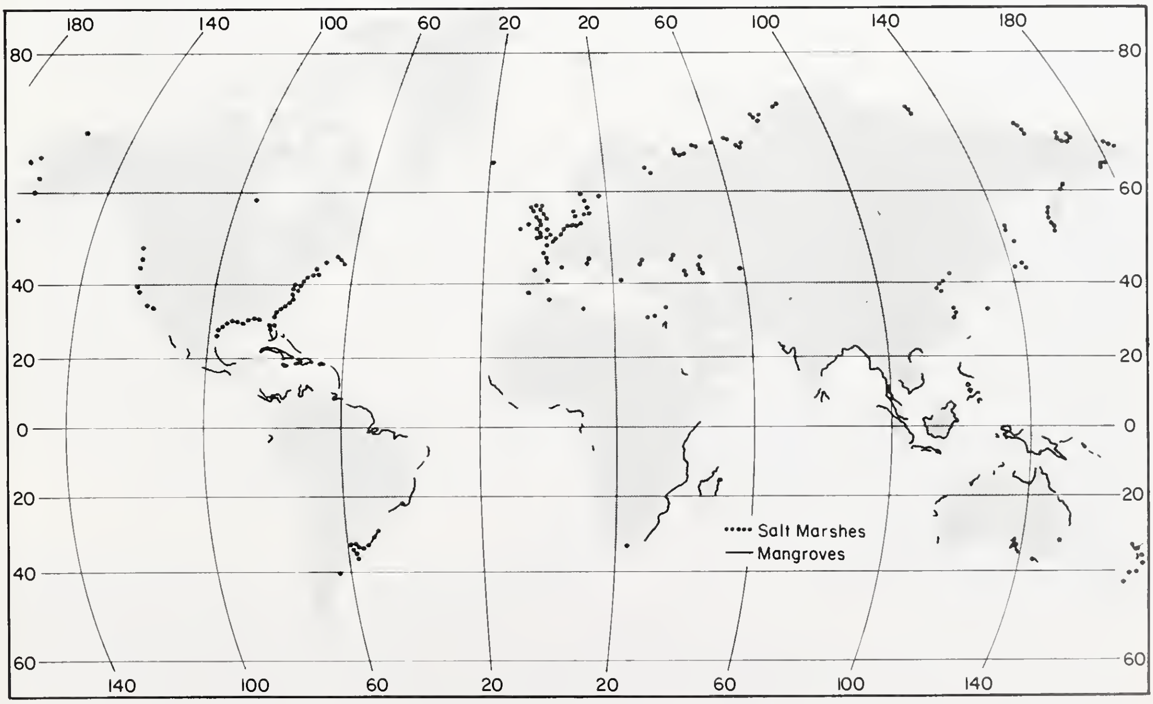


Figure 1. World distribution of well-established salt marshes and mangroves. Both habitats are more widespread, since we used only records from the literature and our own experience. Many places,such as Alaska, the Arabian Peninsula, Baja California, and northern and western Eurasia,are not well represented in the references. Notice, however, the clear demarcation between marshes and mangroves.

evaporation ponds for the production of salt. Also in Thailand and elsewhere in Southeast Asia, extensive acreage of estuarine mangrove has been virtually eliminated by the harvesting of mangrove timber for firewood and charcoal. In Malaya and a few other countries, recently developed management practices permit balanced exploitation of swamps, but elsewhere the decimation continues.

One of the most dramatic episodes in European agrarian history was the struggle for use of the rich soils of wetlands. There is no better example than the well-known diked polders—reclaimed lowlands—of Holland and Belgium. Records of dikes in what is now the Netherlands go back as early as A.D. 1018. In Flanders, poldering was first recorded in A.D. 1111-1115. The construction of polders was in its heyday in the early 1600s and again in the 1800s, spurred by the increased price of grain in Amsterdam and other markets. The polders provided both protection from the sea and needed agricultural land, powerful imperatives in earlier times. Today the balance between the benefits of agriculture and of fisheries in the North Sea is more difficult to evaluate. Flood control no longer requires diking. Additionally, research is underscoring the economic importance of marshes, tidal flats, and inlets, such as the Waddensea in Holland. The Waddensea is now the primary nursery for North Sea fish and the only nursery area available in the North Sea for brown shrimp, a major crop. The current annual return of fish that depend on the Waddensea nurseries is reported to be

Figure 2. Air view of a Cape Cod salt marsh. The entire marsh is drained by the single channel in lower center and a barrier beach protects the marsh. No major fresh-water streams enter this marsh, but elsewhere the major channel is often a river or estuary.

more than $400 million.

Nevertheless, society continues to intrude. Petrochemical complexes, power stations, and extensive new dikes are being planned along the coasts of the Netherlands and West Germany. Pipelines carry oil and gas from the North Sea through the Waddensea, while pollutants from the Rhine River are transported northward into this tidal flat. In the Wash, a very large tidal area in Great Britain, 15 percent of sandbanks and mud flats will be converted into fresh-water lagoons by 2020 through the building of banks 14 meters high. The fresh water is needed to satisfy the projected requirements of southeastern England. All these activities, some critical to human welfare, some not so important, affect the wetlands in which they take place (Figure 4).

There have been some successful attempts in North Carolina, the Netherlands, San Francisco Bay, and elsewhere to construct marshes by planting marsh grasses on dredge spoils and on eroding mud flats. In Guyana, *Spartina braziliensis* has been planted on mud flats for coastal protection. Once the stands of these grasses are established, mangrove seedlings are planted, and the mangroves eventually replace the grasses. With these exceptions, the interaction between people and marshes has resulted in reduced marsh acreage. In Connecticut,

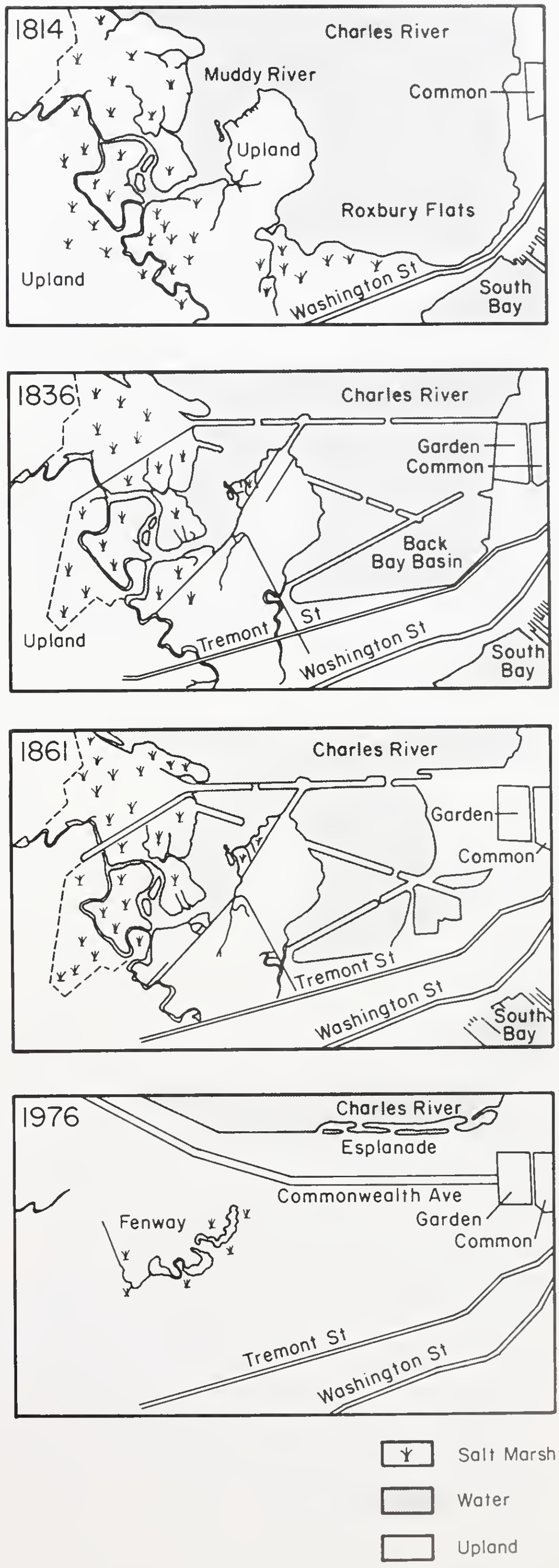


Figure 3. Back Bay, Boston, from 1814 to the present. In 1814, the main part of Boston was situated in the northeast, separated by the Neck from the mainland, where most of the marshlands were located. By 1836, filling was in place to support railroad tracks over the Roxbury flats. The main dam, built of stone and earth fill, was completed in 1821 and used tidal energy to run mills. The reduction of tidal flushing in the Back Bay Basin, the large area in the right center of the map, led to stagnation and stench. Filling continued westward from the Common and northward from Tremont Street. Today, the shore of South Bay has moved to the southwest, all the marshes are gone, and a little water in the Fenway remains from the Muddy River marsh.

Figure 4. Industrial development over a salt marsh in Saugus, Massachusetts. The photo was taken from a solid waste disposal area (foreground) that now covers a substantial part of the marsh.

50 percent of the original marshes have been destroyed, and of the 14,000 acres remaining in 1969, about 200 acres have been filled each year. Not all examples are as striking as Connecticut's, but the trends are similar. Because of the continued threat to marshes and mangroves, it is important to consider the consequences of such widespread reduction in acreage.

Properties of Wetlands

We have already mentioned coastal wetlands as nurseries for commercially important fish. In the southeastern United States, 60 percent of the species use tidal marshes as nursery grounds. A variety of wildfowl and mammals also rear young in marshes and mangroves. The Department of the Interior estimates that in good years up to 200,000 ducks can be produced in northeastern coastal marshes, while 700,000 may be raised in the southern coastal marshes. Many migratory ducks, geese, and other waterfowl use coastal wetlands as resting stations and feeding grounds during their seasonal movements. Other species, such as bluefish or flounder, may make transient use of marshes for feeding, overwintering, or as nurseries (see page 55).

A major portion of the catch of oysters, clams, scallops, eels, alewives, smelt, and other food species is taken directly from salt marshes in this country. In Connecticut, the shellfish industry earned $20 million annually from 1900 to 1920. More recently, the annual income has dropped to $1.5 million, presumably due to reduction of spawning beds. In the small Massachusetts town of Falmouth (population 20,000), where our laboratories are located, shellfish valued at $151,900 were harvested in 1975 from the local marshes and inlets. Shellfish harvests, and therefore marsh conservation, are of importance to the economy of coastal towns.

A further property of coastal wetlands is their ability to scrub contaminants from tidal water. Since most marshes are in estuaries or have ground water flowing into them, the ability to retain contaminants may prevent further transport of pollutants to the sea. For example, researchers in Fiji and Hawaii have found that inorganic nitrogen released by a waste treatment plant upstream in a mangrove estuary was reduced by 56 percent by the time the contaminated water entered the sea after passing through mangrove swamps (Table 1). These results are indirect, since river sediments might trap nutrients even if the swamps were not present.

We have conducted experiments involving the addition of sewage-based fertilizer to marsh plants in Cape Cod and found that both nutrients and metals were retained (Tables 2, 3). The data showed that the retainment of nutrients was high and depended on the amount added. Retainment of metals varied with the kind of metal but was especially high in the case of copper, iron, and lead. Marshes and mangroves, then, seem to have the ability to retain nutrients and heavy metals. We also have evidence for retention of chlorinated hydrocarbons and perhaps pathogens brought into marshes by contamination. The major component in contaminant retention appears to be the mud, the surfaces of whose finely divided particles provide sites for adsorption.

Nitrogen retainment by marshes is especially important, since large inputs of this element can lead to algal blooms in coastal water, as happened in Moriches Bay in Long Island, New York, where agricultural wastes created extreme nitrogen enrichments. Nitrogen entering wetland systems follows two major routes. The mud below the surface layer bears little oxygen and thus favors

Table 1. Reduction of nitrate (NO_3-N) and ammonium (NH_4-N) from a sewage treatment plant after passage through a mangrove estuary. The plant is 2.5 kilometers upstream from the river mouth and the river is lined with mangrove swamps. (After Nedwell, D. B. 1975. Inorganic nitrogen metabolism in a eutrophicated tropical mangrove estuary. *Water Res.* 9:221-31)

	Amounts of Inorganic Nitrogen (milligram atoms nitrogen per day x 10^6)			
	Output from treatment plant	Net export from river	Decrease due to passage through mangrove estuary %	Mean %
NO_3-N	1.30*	0.77	41	30
	0.12	0.10	19	
NH_4-N	0.80	1.20	54	63
	1.10	0.42	72	
DIN**	2.10	1.20	43	56
	1.41	0.42	69	

*The two values are from two separate sampling dates.

**Dissolved inorganic nitrogen. Apparently nitrite (NO_2-N) was very low and was not considered.

Table 2. Retention of ammonium (NH_4-N) and phosphate (PO_4-P) by salt marsh plots. The nutrients were provided at two dosages of sewage-based fertilizer.

	Amount of fertilizer added (grams per square meter per week)	Percentage of added nutrients retained in marsh	
		NH_4-N	PO_4-P
Plot 1	25.2	79.7	91.1
Plot 2	8.4	95.6	84.1

Table 3. Retention of metals by two kinds of salt marsh habitats within experimental plots. The metals were provided by experimental additions of sewage-based fertilizer. Low marsh is dominated by *Spartina alterniflora,* while *S. patens* and *Distichlis spicata* are the main grasses in high marsh. (Data compiled by A. Bourg)

	Percentage of added metal retained by marsh	
Metal	Low marsh	High marsh
Copper	60	100
Iron	80	100
Lead	55	100
Manganese	55	60
Nickel	45	65
Zinc	20	45
Cadmium	20	35
Chromium	20	50

the activity of bacteria that convert inorganic nitrogen into nitrogen gas. This process of denitrification is probably the primary way that eutrophic waters are scrubbed of nitrogen by liberation of nitrogen gas into the atmosphere. The second major pathway for the remaining nitrogen is into sediments and then plant production. Plant productivity in marshes is among the highest in the world, equalling extensively managed agricultural areas. Since the growth of marsh grasses is limited by the supply of nitrogen, the more nitrogen that is scrubbed from tidal water by the marsh, the more grass can grow.

Little of the plant production is consumed by animals while the plants are still alive. Instead, mangrove leaves fall onto the water where tidal flow eventually moves them to deeper waters. In marshes, the grasses die and become food for bacteria and fungi, which in time are consumed by a variety of animals. Reduction in size of the grass particles takes place, facilitating their being flushed out of the marsh. Through this export wetlands provide organic matter for the numerous detritus feeders, such as shell and fin fish found in coastal waters. Given this high concentration of nutrients and organic particles, it is natural that experimental work in estuarine aquaculture of shellfish should be undertaken. Initial systems employing dead mangrove branches or cut squares of old rubber tires threaded on a line as settlement surfaces for oysters work well within mangrove swamps in Cuba and Puerto Rico. Marketable shellfish can be harvested within 6 to 8 months, with the advantage of very low technological requirements (Figure 5). The shellfish wardens of Falmouth and neighboring Bourne have had success in rearing oysters and clams in tidal channels within salt marshes.

The Cost of Reduction

Coastal fisheries, migratory birds, natural treatment of contaminated waters, potential sites for aquacultural development—these are some of the areas affected by reduction of coastal wetlands. Others have to do with stabilization of shorelines, protection and repair from storm damage through natural re-establishment of marsh plants—even the possibility, borne out by our retainment studies, that marshes could be incorporated in tertiary treatment systems for disposal of sewage wastes.

We have not discussed the aesthetic aspects of wetlands, since these intangibles are difficult to gauge in the consideration of the value of marshes. Prosaic dollars-and-cents arguments are likely to be more convincing. Attempts to put a price on a unit of marshland have been made, using some of the wetland functions mentioned earlier. Based on the fisheries, waste treatment properties, and aquaculture potential, researchers in Georgia came up with a very speculative annual return of $4150 per acre of marshland. This more or less means that in the absence of marshes, society would have to provide that amount of money to accomplish what the marshes are actually doing. It is very hard, however, to make the economic argument for wetlands compelling, since coastal wetlands can rarely compete with other economic incentives. For example, in the Hackensack Meadowlands of New Jersey, one acre of marsh may be worth $100,000 to industrial developers. Similarly, the Waddensea wetland cannot offset the massive economic and political interests involved in oil production and transport. Yet other social values must enter the equation. Onshore jobs related to coastal fisheries or ways of life based on the yield of wetlands are examples. Others are the aesthetic benefit of open greenbelts in a crowded world and the irreplaceable nature of a food-producing wetland in a time of costly and scarce food supply. Perhaps we are arriving at a time when these factors should be recognized and considered in the management of resources.

In most coastal areas of the United States, wetlands can be owned by individuals, yet the functions and properties of wetlands—and their importance to society—are such that common ownership and management for the common good

*Figure 5. A red mangrove (*Rhizophora mangle*) swamp in Sierra Leone. The tidal range is shown by the height of oysters (*Ostrea tulipa*) settled on the roots and trunks of the trees. (A. G. Humes)*

Sidney E. King's painting of Jamestown, Virginia, as it may have appeared a few years after settlement and before widespread filling and the disappearance of wetlands. (Courtesy National Park Service)

would seem to make better sense. It is hard to see how the average individual owner of a parcel of wetland, if he behaves in an economically rational fashion, could be interested in marsh conservation. Except for aesthetic aspects, the owner's main interest would be to build his dock or house or to sell to a developer, not the welfare of coastal fisheries.

Clearly, there are exceptions. Many owners of private marshland do work to maintain the integrity of their property. Certainly, conservation easements, such as those enacted in Massachusetts, are helpful in redressing the economic disadvantage of maintaining wetlands in their original state. We are merely arguing that the political and economic system in the United States does not naturally provide incentives for conservation. Our experience in Massachusetts, a state with very good wetland laws, is that the priority of private ownership is so established that little can be done against the parcel-by-parcel destruction of marshlands. The one sure solution seems to be municipal or state purchase of wetlands. Of course, this runs headlong into political and economic interests and is an issue that can and should be decided by the voting public.

In the tropics mangroves are faring worse than temperate latitude marshes. In most less developed countries, little room is allowed for long-term considerations, which by necessity take second place to attempts to improve the local economy. Awareness of environmental problems seems to be rising in less developed countries, however. In time, reasonable management policies, comprising conservation as well as aquacultural and other uses, may appear. It is not clear, though, that such measures will be enacted before wetlands have largely disappeared.

Ivan Valiela is an associate professor and Susan Vince is a graduate student in the Boston University Marine Program, Marine Biological Laboratory, Woods Hole.

Suggested Readings

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Pollution History of Estuarine Sediments

by Edward D. Goldberg

Industrial discharge in 1973 polluted this salt marsh at Middleton, Rhode Island. The law now requires every industry to obtain a permit regulating its discharges. (Hope Alexander/Courtesy Environmental Protection Agency/Documeria)

Many forces can change the structure and composition of the estuarine environment. In addition to natural events like hurricanes, earthquakes, and typhoons, there are the agricultural, social, and industrial activities of man that can introduce new substances to this system where river and ocean waters mix. Some of these substances, or pollutants, are accommodated in the sediments; others are transported to the open ocean. The flow rates of the pollutants entering the estuary may be recorded in its deposits, and such records may be of great use to those responsible for the management of this marine resource. In addition to describing present-day and past entries of these materials to an estuary, in principle we may be able to predict future ones with a knowledge of present and past productions and estimates of future production, for a given pollutant.

What are the characteristics of pollutants that may be recorded in estuarine sediments? First of all, the material must have a persistence in the environment. Radioactive substances with short half-lives, organic materials easily degraded by microbial action, or chemically unstable molecules may leave no record of their presence in the coastal system. On the other hand, stable materials, in either dissolved or particle form, that are rapidly removed to the sediments provide favorable case studies. Estuaries display high levels of biological activity, so that pollutants may be transported to the sea floor in fecal matter, organic remains of organisms, and skeletal materials. Thus, highly reactive elements like lead, copper, and zinc, and materials taken up by living organisms like DDT, PCBs, and petroleum components, are examples of pollutants whose historical entries to estuaries have been measured.

Not all sediments faithfully record the flow rates of pollutants. Those low in organic matter may maintain in their upper strata a community of organisms whose burrowing activities can distort or perhaps even destroy the pollution record. On the other hand, deposits with high levels of organic matter, which are often lacking in dissolved oxygen (anoxic) as a result of the oxidation of organic materials by bacteria, do not support such burrowing organisms and can therefore provide a reliable pollution history. One indication of the absence of animal activity (bioturbation) is the presence of annual or semiannual sediment layers of different compositions; that is, more plant remains enter the sediments in the spring blooms than during the less productive seasons of the year.

Geochronology

In order to ascertain the amount of a pollutant entering a deposit per unit time, the age of the strata (its geochronology) must be determined. Time assignments can be accomplished in several ways, including radiometry, stratigraphy, and physical evidence from dated events such as hurricanes and typhoons. The reliability of age assignments can be enhanced by the use of two independent techniques of geochronology, where possible.

The natural radioactive nuclide most frequently used in dating estuarine sediments is lead-210 (Pb-210). Its half-life of 22.4 years allows periods of a century or so to be studied in the sedimentary column inasmuch as its decay over four such half-lives can usually be measured. Pb-210 is separated from its parent in the uranium-238 series, radium-226 (Ra-226), through diffusion of the rare gas nuclide radon-222 (Rn-222) from crustal rocks to the atmosphere, or through sorption on solid phases precipitating to the sediments without significant amounts of Ra-226. In the former case the Pb-210 is brought to the marine system in rain or with dry fallout.

Radionuclides produced by man as a consequence of nuclear weapons testing have been used successfully to place time frames in estuarine sediments. Radioactive debris such as the fission products strontium-90 and cesium-137, induced activities such as cobalt-60 and zinc-65, and fuel remnants such as the transuranics plutonium-239 and americium-241 can in principle be utilized (Figure 1). This radioactivity is introduced in large part to the stratosphere from surface and atmospheric tests where it remains for about a year before returning to the earth's surface. Following periods of intense testing in the late 1950s and early 1960s, fallout maxima of radioactive debris were observed in 1959 and 1963. Estuaries received direct fallout of this radioactivity as well as that which fell on the earth's crustal rocks and soils and was subsequently remobilized to the marine environment by winds or rivers. Thus, depth profiles of plutonium, for example, in estuarine sediments often show increasing amounts in strata deposited from 1954 to the present time. The first measurable quantities are usually in the 1954

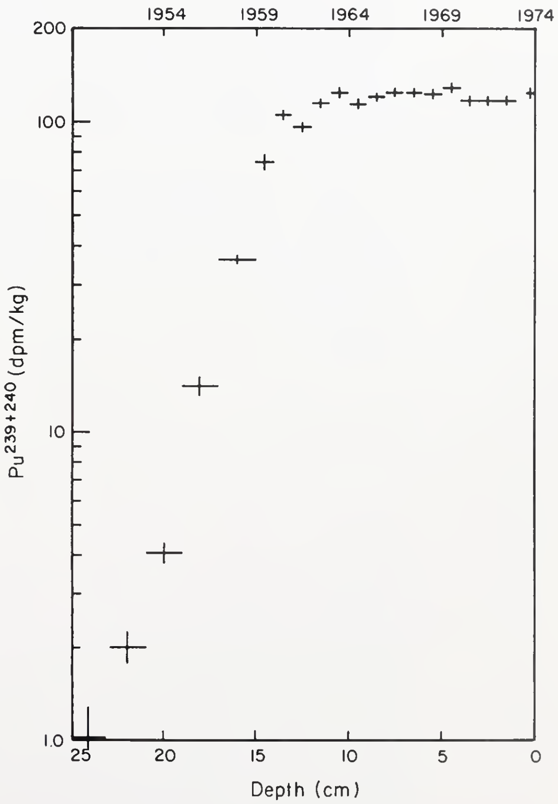

Figure 1. Plutonium concentrations in strata from Box Core 4708-2813 taken in Narragansett Bay. The appearance of these transuranic nuclides at 21-23 centimeters heralds the time of 1954 or so, when they first became evident in marine sediments. On this basis, the 22-centimeter level can be assigned an age of 1954, which is consistent with the time of the hurricane movement of shells (see Figure 2).

deposits and can be used to mark that year in the sedimentary record.

Stratigraphically, age assignments can sometimes be based on features such as varves, annual or semiannual deposits typically consisting of two layers of different materials. Varves are the result of seasonal differences in composition of sedimenting materials. For example, riverborne particulates may be carried to the estuary primarily during spring floods, while atmospherically transported particles may dominate during the more arid summer months. The differences in composition of these seasonally deposited layers can often be detected by x-ray. Sometimes they are evident visually.

A catastrophe such as a hurricane, typhoon, or earthquake can move solid phases about an estuarine system and in so doing introduce time-marks into the deposit. The displacement of gastropod and bivalve shells during a 1954 hurricane at Narragansett Bay introduced to some sediments a record of this event. In one deposit (Figure 2) the shells are found between 15 and 22 centimeters depth. Pb-210 and plutonium geochronologies of adjacent strata are in accord with the 1954 date. By extrapolating the Pb-210-derived accumulation rate of 1 centimeter per year to 22 centimeters, one can date this stratum at 1952, within two years of the bivalve age. Plutonium is first measurable at 21-23 centimeters, which sets the year for the deposition at 1954. All three dating methods give ages in agreement within a period of several years over the twenty-year time frame.

The recovery of undistorted sediment cores from estuaries is of paramount importance in decoding the pollution record. Hydraulically slowed box cores provide relatively undisturbed materials. The slowed entry results in the capture of both the deposit materials and the overlying waters. As a result there is an increased tendency to collect the surface and near-surface sediments. Immediately after collection in our investigations, the core is quick-frozen and stored at -20°C.

This last operation, which solidifies the material, allows ready transport and sectioning. Still, there are minor distortions. The interstitial water, in going through a temperature of minimum volume around 4°C and in subsequent expansion, forces the central parts of the core upward (Figure 2). In order to properly sample discrete strata, it is essential to have an x-ray of the section to determine their placement in the core.

Lead in Sediments

Estuarine deposits accommodate riverborne particulates and solids eroded from the shore, the organic and inorganic remains of organisms, and, sometimes, materials introduced through outfalls. To a lesser extent, atmospherically transported phases also enter estuarine deposits. The determination of a particular transport pathway for a given pollutant can be vexing. For example, the primary anthropogenic source of lead to the environment is the combustion of lead alkyls in gasolines, where they act as antiknock agents. Following release from exhausts of automobiles, the lead particles are wafted about in wind systems. Eventually, coastal waters adjacent to centers of high population may receive these lead particles in a variety of ways. Lead carried by the atmosphere is removed by rain and by dry fallout to the ocean surface or to the land, where it can subsequently be transferred to the oceans by rivers or storm sewers. During the dry season, some lead can be moved by the small amount of water that flows as a consequence of such activities as watering lawns–the so-called dry runoff. Finally, the discharge of treated sewage can add a significant amount of man-mobilized lead to the coastal ocean.

Huntzicker and his colleagues (1975) at the California Institute of Technology studied the flow of lead through the Los Angeles Basin into the coastal waters and presented the following data for the early 1970s:

Input Route	*Tons/Year*
Storm runoff	140
Dry fallout	120
Rainout	30
Dry runoff	10
Municipal sewage	230

The total delivery of 530 tons of lead per year compares with the 8760 tons of lead per day burned in the area as gasoline antiknock additives. Although the semiarid climate of the region and the intensive use of automobiles make these figures site-specific, the data nevertheless indicate a type of impact on a coastal environment that may be recorded in the sediments. Lead is a highly reactive element in the marine system and can be transferred to the deposits by its involvement in biological cycles.

In our laboratories we have measured the lead accumulation rates in basins adjacent to the Los Angeles area at distances of 30 to 100 kilometers from the coast, and they are in agreement with the fluxes calculated from the above data, assuming a coastal depositional zone of 4400 square kilometers. The history of this input is recorded as a function of depth in the sediments

Figure 2. X-ray of sediment taken in Narragansett Bay (Box Core 4708-2813). Note layer of shells at 15-22 centimeters depth that have been associated with the 1954 hurricane. The ice crystals and the buckling of the uppermost levels of the core are a consequence of the freezing process.

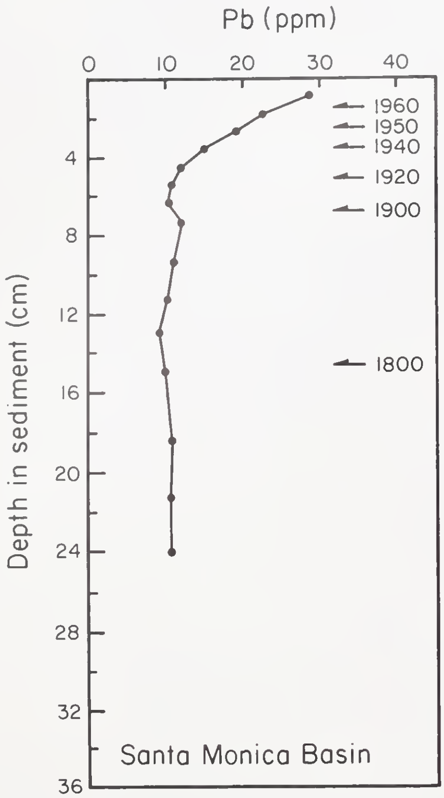

Figure 3. Lead concentrations in sediments from the Santa Monica Basin off Southern California. Increased levels appear in strata deposited after 1940. (After Chow et al., 1973. Copyright 1973 by the American Association for the Advancement of Science)

(Figure 3) as well as by the isotopic composition of the lead. This anthropogenic lead first became evident in the 1940s and has a unique isotopic composition compared to that of lead deposited before its extensive use as a gasoline additive. Studies on the fluxes to basins as a function of distance from the coastline show a fallout with respect to the square of the radius, indicating the intensive impacts are nearshore.

Hurricane Agnes in Chesapeake Bay

Of the larger estuaries on the eastern coast of the United States, Chesapeake Bay is one of the most frequently studied because it is greatly affected by millions of residents of Maryland, Delaware, Virginia, and the District of Columbia. In addition, the tropical storm Agnes caused more sediment to be discharged during one week in June 1972 than during the past several decades (Schubel, 1974). Is hurricane Agnes recorded in the sediments? Did this catastrophe destroy or alter the pollution records in Chesapeake sediments?

In collaboration with scientists from Johns Hopkins University, we have sought answers to these questions through an examination of four box cores to depths of 70 centimeters taken in 1975 (Figure 4). Two samples were taken near the outfall of the Susquehanna River: one, close to the outfall of the Potomac River; and one, midway between the two discharge areas. Through attempts to establish time frames for these deposits and through chemical, mineralogical, and physical analyses of the sediments, natural and pollution phenomena were found to be recorded.

The first 20 to 30 centimeters of the two southerly cores and the entire lengths of the two northerly cores were essentially uniform in all properties. There were no decreases in the concentrations of the radioactive species, like Pb-210, which should have shown an exponential decrease with depth, had there been continuous accumulations. Herein is the record of the hurricane. On the other hand, the two southerly cores, at depths from about 20 to approximately 70 centimeters, did have time frames that could be developed with Pb-210 or Pu-239+240 geochronologies. In these cases, there were increases over the past several decades in the concentrations of such heavy-metal pollutants as lead, copper, zinc, and nickel. The anoxic nature of the cores had preserved the pollution history.

Perhaps of even greater interest was the observation that the two southerly cores recorded different intensities of pollution, presumably reflecting entries from two different river systems. The sediment adjacent to the Potomac received smaller anthropogenic fluxes of heavy metals, as well as their natural fluxes, than did the more northerly deposit, which received its solids primarily from the Susquehanna. In addition, the intensities of the fluxes were less than those from the Susquehanna, which is in accord with the sense that the Susquehanna delivers around 90 percent of the sedimentary solids to Chesapeake Bay.

Records of Fossil Fuel Combustion

The amounts of material released to the environment from the combustion of fossil fuels, coal, oils, and lignite, are comparable to those transported in rivers during the weathering processes. Burning introduces the substances to the atmosphere, where washout and dry fallout processes can return them to the earth's surface. Such elements as arsenic, mercury, cadmium, tin, antimony, lead, zinc, thallium, silver, and bismuth, whose compounds are often relatively volatile, may be preferentially mobilized. Since the principal sites of fossil fuel combustion are in the Northern

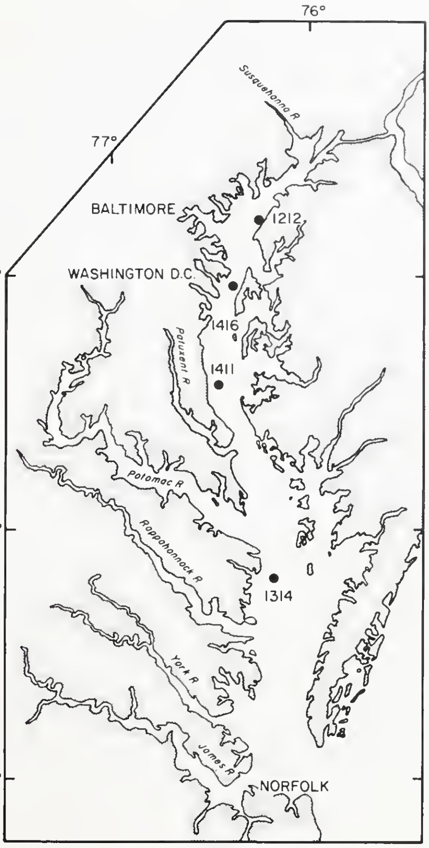

Figure 4. Locations of four box cores taken in Chesapeake Bay in 1975.

Hemisphere, the impacts on coastal marine waters are most evident at these latitudes.

Scientists in Germany (Erlenkeuser et al., 1974) have studied the sediments of the western Baltic coast and have found that cadmium, lead, zinc, and copper are enriched in sediments recently deposited. Concentrations of other metals such as iron, manganese, nickel, and cobalt are unchanged throughout the lengths of the cores. The time frame in these deposits was introduced with carbon-14.

The enrichment of heavy metals in the sediments is associated with coal burning (coal combustion potentially mobilizes 70-200 times more of these metals than oil burning) on the basis of the relative contents of the metals in coal and in sediments and on the amounts of coal burned. The measured values in the upper levels of the sediment corresponded to a mixture of 93 percent sediment and 7 percent coal ash, where the unaltered composition of the sedimentary components was based on those of prehistoric strata. The anthropogenic input of heavy metals then corresponded to the European coal production, and presumably utilization, over the past several centuries (Figure 5).

Records of Industrial Activity

The metal composition in sediments of the Puget Sound estuarine system have been perturbed by two major human activities: a copper smelter and a chlor-alkali plant. The former discharged large amounts of arsenic and antimony; the latter, substantial quantities of mercury. Where natural levels of arsenic ranged between 3 and 15 parts per million and of antimony between 0.3 and 1.0 parts per million in the deep sediment, the values in contaminated surface strata were as high as 10,000 parts per million. On the basis of the geographical distributions of these materials, transport was attributed to both wind and water (Crecelius et al., 1975).

The mercury levels of the surface sediments adjacent to the chlor-alkali plant were elevated a thousandfold over the natural background values during the years in which the element was discharged from this industrial activity. The pollutant and natural mercury are associated with easily oxidizable organic matter. On the other hand, naturally occurring arsenic and antimony are bound generally to extractable iron and aluminum compounds, whereas these two elements in polluted zones are nonextractable and appear bound in rather stable chemical forms. Thus, whereas arsenic and antimony mobilized by man are relatively inert in the deposits, the mercury can be mobilized in

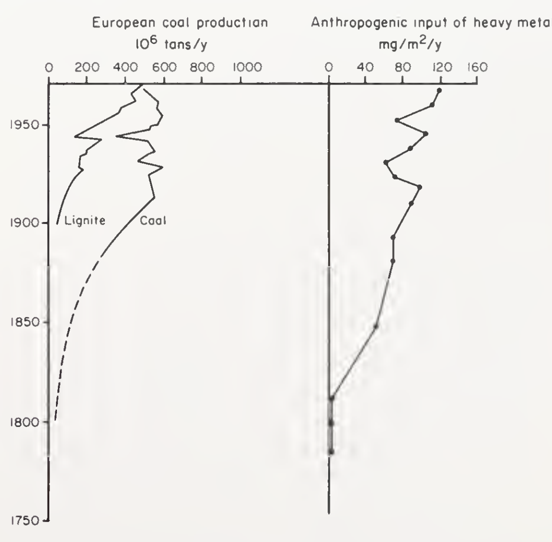

Figure 5. European coal production compared with the anthropogenic flow of heavy metals into Baltic Sea sediments. (After Erlenkeuser et al., 1974)

principle by changes in the oxidation-reduction conditions.

DDT and PCBs

Sewage outfalls can deliver to the coastal environments toxic substances that can alter the makeup of plant and animal communities. For example, until 1972 fairly large quantities of DDT were released into the Los Angeles municipal-waste system. Hom and his colleagues (1974) estimated that 19 metric tons were discharged in 1971. Atmospheric fallout and agricultural runoff were estimated to add several metric tons per year. The history of these releases is well recorded in the coastal sediments, where measurable quantities of DDT degradation products appear in the strata deposited after 1952 (Figure 6). Similarly, the industrially used polychlorinated biphenyls (PCBs) have entered coastal waters primarily via sewer outfalls (for 1970-71, 10 metric tons per year) as compared to surface runoff (0.25 metric tons per year for the same time period). PCBs were first noted in the 1945 strata.

These inputs have been associated with the population decreases of the California brown pelican off Anacapa Island and with reproductive failures in sea lions through premature births and abortions. The victimized birds laid eggs with thin shells that were liable to fracture and breakage. Many of the eggs collapsed during the incubation period. High levels of DDT and its metabolites were found in the birds. Similarly, there were enrichments of both DDT, and its metabolites, and PCBs in the premature sea lion pups and their mothers. However, there were elevated concentrations of other chemicals, like cadmium, bromine, selenium, and mercury, that may have contributed to the situation. Possibly, the problem had natural, not man-instigated, causes. Since the early 1970s, inputs of DDT and PCBs have been markedly decreased due to restrictions on their use.

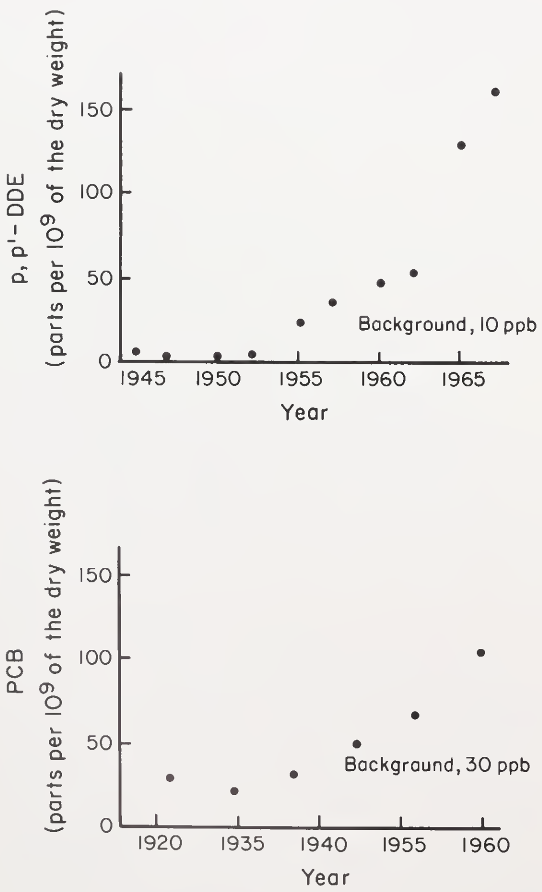

Figure 6. Deposition of DDE and PCB in dated sediments of the Santa Barbara Basin. (After Hom et al., 1974. Copyright 1974 by the American Association for the Advancement of Science)

Radioactive Wastes

The management of radioactive wastes from nuclear reactors and from nuclear reprocessing plants is a major concern in most national energy programs. Since many installations are located in estuarine areas and discharge low-level wastes to the coastal waters, an understanding of the behavior of artificial radionuclides is essential (*Oceanus,* Fall 1974). The transuranic elements (all elements heavier than uranium), especially plutonium, have been the object of several recent studies, primarily because of the question of their effects on public health. The most extensive investigations have been carried out in the area of the northeast Irish Sea where there are nuclear installations, including a reprocessing plant at Windscale, England. Measurements of plutonium in seawater, human foods (such as fish and shellfish, and the seaweed *Porphyra*), and sediments done by Hetherington and his colleagues (1975) indicate that 96 percent of the introduced plutonium is removed to the sedimentary column in the immediate vicinity of the outfall. This finding establishes the importance of the sedimentary column in the future behaviors of this transuranic.

The plutonium concentrations in surface sediments relative to the overlying filtered waters, to distances of slightly over 100 kilometers from the outfall, are related to the mineralogy and the size distributions of the particles. There were no remarkable enrichments of plutonium in the sediments closest to the outfall, which led the investigators to suggest that a large fraction of the

Water from a pulp mill circulating in Bellingham Bay, Puget Sound, Washington, 1973. (Doug Wilson, Courtesy Environmental Protection Agency/Documeria)

plutonium is being removed from the vicinity altogether. Concentrations of plutonium in estuarine sediments in the area appeared to decrease exponentially with depth to distances of about 24 centimeters. No time frame was introduced into the sedimentary strata. However, there is a possibility that the sedimentation rate is too low to account for the plutonium at these greater depths. There may be a reworking biologically of these sediments with a resultant downward displacement of plutonium.

However, of greater importance is the estimate that a major fraction of the plutonium discharged from the Windscale operation is at present associated with the seabed. This induction is of great importance in accessing the longer-term consequences of the radioactive discharges to man and to marine ecosystems.

Fate of Pollutants

Not all of the pollutants that enter an estuary are retained in its sediments. Some enter the open ocean. There are only a few investigations that have addressed themselves to the question of what percentage of a given substance entering an estuarine system leaves that system. Perhaps the most detailed study to date is that of Windom (1975) on the Savannah River salt-marsh estuary. Windom compared the fluxes of metals carried into the Savannah system by nine rivers with the amounts precipitating annually to the sediments. The differences were taken to be the metal inputs to the open ocean system. Of the five metals studied—iron, manganese, cadmium, copper, and mercury—the last three could have entered the estuary as a consequence of man's activities.

Essentially all of the dissolved iron precipitated in the estuary, while practically all of the dissolved copper and cadmium went to the open ocean. The net flux of dissolved mercury through the estuary was greater than its river input, suggesting that there must have been some release of the metal that was adsorbed to the particulate matter. The particulate matter, carried by the rivers, and its adsorbed materials stayed within the estuary. Although this conclusion may be specific only to this rather unusual salt-marsh system, the general method of determining which substances the Savannah estuary retains, and in what amounts, may be applicable to other areas.

Conclusion

The zone where the river meets the ocean is one of man's most important resources. And yet human activities are changing the form and composition of estuarine sediments. The history of some of these changes is recorded in the sediments.

Challenges to or permutations in the integrity of marine ecosystems may be more subtle and hence difficult to detect. Work from the CEPEX project (Controlled Ecosystem Pollution Experiment), sponsored by the U.S. Office of the International Decade of Ocean Exploration (*Oceanus,* Fall 1974), suggests that there may be a predictable succession of species in a community subjected to an environmental stress, be it copper, mercury, or petroleum. There is usually a weakest species, the first to fall victim to the alteration of the environment. This situation has also been observed in terrestrial communities.

Estuaries adjacent to industrialized societies are subjected to a variety of stresses—in sewer effluents, industrial discharges, atmospheric fallout, dumping, and accidental releases from ships. If it is the case that many stresses act in a similar way on a population, it is conceivable that serious alterations to community structure can take place. Such permutations may even extend to the adjoining coastal oceans. Clearly, the possibility of such an occurrence requires serious assessment.

The estuarine zone has become more and more attractive to marine chemists, because it is the site of some of the most dramatic chemical reactions in the ocean system. Many of these reactions are a consequence of river-ocean interaction or of the often high biological productivity. Each estuary probably is a chemical entity unto itself, unique because of the particular terrestrial and marine chemistries that give rise to it. Man's alterations, as well as natural processes, deserve further study in order to manage properly these important zones.

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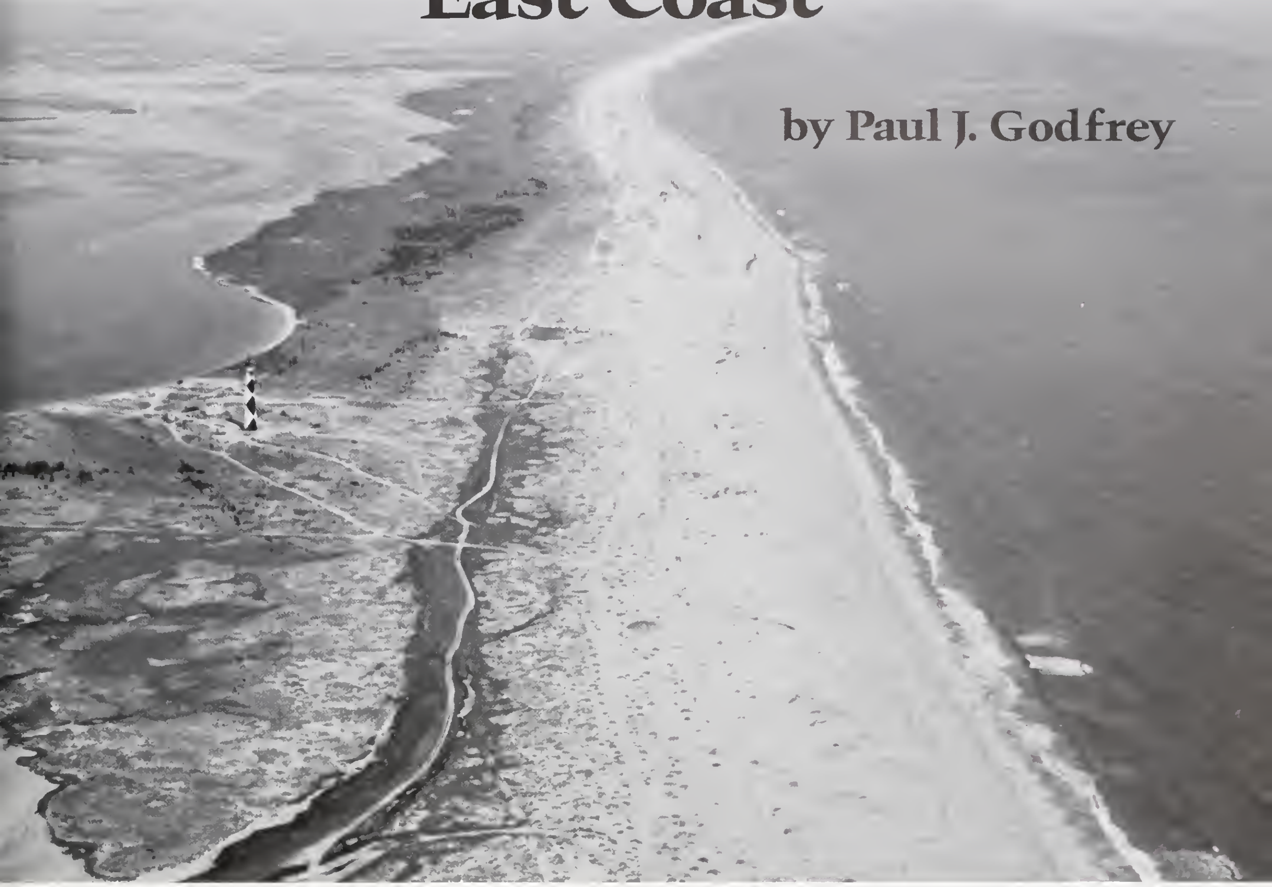
Barrier Beaches
of the
East Coast

by Paul J. Godfrey



A critical part of many estuarine systems is the long finger of land that makes up the seaward boundary of the estuary and protects it from the direct onslaught of the sea. These low-lying strips of land are barrier beaches. The usual definition of an estuary is a zone of transition where fresh water flowing to the ocean mixes with salt water. The seaward end of the estuary is often a large bay, sound, or lagoon connected to the sea by means of inlets, particularly on the East Coast of North America. The land on either side of the inlet is a barrier beach.

The existence of most estuaries depends on the presence of barrier beaches on the ocean side. This is particularly true for bay-or-lagoon type estuaries. These beaches, as the name implies, protect the estuarine environment from waves and currents that would otherwise demolish the delicate ecological mechanisms in the waters behind the barrier. What happens on the barrier beach can have a direct effect on the conditions in the estuary. Barrier beaches are dynamic, continually changing structures; under present conditions, they are migrating landward. The mechanisms of migration

Aerial view of Cape Lookout National Seashore, North Carolina, with its diamond patterned lighthouse. This marks the southern end of the Outer Banks, one of the most extensive barrier island systems in the world. Core Banks sweeps northeastward to Cape Hatteras beyond the horizon; Barden's Inlet separates Core Banks from Shackleford Banks on the left. The shallow and highly productive estuarine waters of Core Sound separate the Banks from the mainland. The eastward migration of Barden's Inlet, artificially maintained by dredging, is threatening the survival of the lighthouse, a National Historical Landmark, built in 1859.

Figure 1. A Northeastern barrier spit created by the erosion of glacial deposits and the transport of sand by littoral drift from right to left. Behind is a lagoon and river estuary draining to the sea through the inlet.

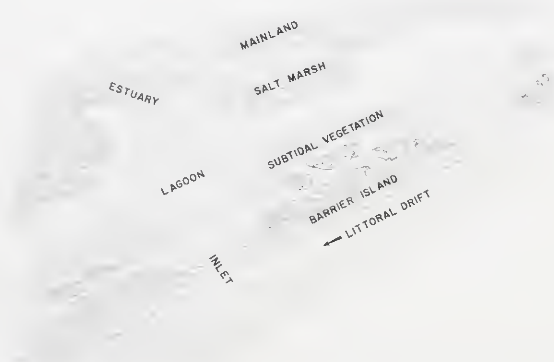


Figure 2. Barrier islands and inlets found along the central and southeastern United States coast.

have an effect on the aquatic environments behind the barrier, the places into which the barrier beach moves.

Nearly all estuarine systems have barrier beaches associated with them. Only the very large estuaries, such as the Chesapeake and Delaware systems, lack barriers where they open into the ocean; and even the large systems have barrier beaches along portions of the estuary. Barrier beaches are rather common structures wherever waves erode sediments and the waves are of sufficient force to carry these sediments along a beach to a place of deposition. Barriers are therefore the product of wave action and erosion in one region and deposition in another. They also are the result of storm, tides, and wind—all features of the land/ocean interface.

In addition to protecting estuaries, the barrier beach system is of considerable importance to the whole coastline, particularly if the coast is low. The barriers protect the mainland from severe wave attack during storms, and slow down the floods from storm surges. They create protected harbors where coastal towns can develop.

The survival of estuaries depends, at least in part, on the survival and natural functioning of barrier beaches. Already, many beaches have been so modified by development that they can no longer respond to the oceanic forces that dictate the terms of survival. It is ironic that the very section of lagoonal estuary most critical to survival is that portion which is often the first to be developed—the ocean beach. Various conservation programs are underway to halt, or at least slow down, the indiscriminate development that has marred so many barrier beaches.

Structure of a Barrier Beach

The term "barrier beach" includes barrier spits and barrier islands. A barrier spit (Figure 1) is a long finger of land, consisting of an ocean beach, dunes, and a marsh on the back side. It extends out from the end of a shoreline, which was the original source of sediments making up the spit. In most cases, the spit will still be attached to the source. It grows out across the mouth of the estuary or bay as waves erode the sediments on the updrift side of the bay and the sand is transported in the general direction of the average wave approach by littoral drift. Thus, the spit grows downdrift: the direction of the growth depends on the average wave angle. Along most of the East Coast, this direction is either south or west.

If a spit is breached by an inlet, or series of inlets, then barrier islands are formed. The barrier island is usually much like a spit, although in some cases much larger and wider (Figure 2). But not all barrier islands are derived from spits. It is important to note major distinctions between various types of barrier islands. Large barrier islands have spits flanking either end of the island and extending into the inlets.

The physiographic structure of a barrier consists of intertidal ocean beaches, dunes, barrier flats, intertidal salt marshes and flats (Figure 3). The arrangement of these parts is fairly predictable, although the exact proportion of one part compared to another can vary considerably. Some barriers have very wide beaches, others very narrow. Certain barriers consist mostly of sand flats and a few dunes, while others are mainly composed of dunes. The intertidal areas behind a barrier may feature extensive marshes while on others the marshes may be greatly reduced. In general, the zones of a "typical barrier beach" can be described as follows:

Intertidal Ocean Beach

What most people call "the beach" is the highly variable sand and gravel structure on which ocean waves lose their energy. It is a habitat in which the sand is constantly in motion and is the first line of defense of the estuarine barrier. The ocean beach consists of three parts: the nearshore, foreshore, and backshore. The nearshore contains two sand ridges that function in the sand budget of the beach: the inner bar, not exposed at low tide, and the "ridge" that is exposed. Between each rise are depressions—the "trough" between the inner bar and the ridge, and the "runnel" between the ridge and the foreshore. At low tide, the runnel carries wave swash that comes over the ridge back to the deeper water. The beginning of the foreshore is marked by the "step," a wave scarp cut at low tide, and rises to the berm crest, usually the highest part of the beach. The backshore slopes back from the berm crest to the dunes. The shape of the beach and the width of the berm at any given time depend on the wave energy regime. During low energy periods, primarily in summer, the beach is wide and steep as waves move sand from the inner bar to the foreshore. During high wave energy periods, the waves move sand from the beach to deeper water and the beach becomes narrow and slopes gently. This pattern of erosion and deposition is typical of summer and winter cycles, or stormy versus fair weather periods at any time of year.

Because the beach is in nearly constant motion, sessile plants and animals cannot survive in this habitat, particularly when wave energies are high. Instead, beach organisms are adapted to constantly changing conditions and consist of animals that can roll around in the sand and rebury themselves, such as mole crabs and coquina clams. A distinct community of microscopic animals and unicellular algae lives between the grains of sand on the beach. Bacteria play a major role in the beach ecosystem by breaking down the vast quantities of detritus that wash ashore, mostly algae from the sea and eelgrass and cord grass from the estuaries behind the beach.

Drift lines deposited on the beach by high tides are often precursors of new dune lines in addition to providing organic detritus for the beach ecosystem. Fragments of dune plants washed ashore with the drift are buried by blowing sand and regenerate the following spring. Besides beach grass and dusty miller, which are perennials, seeds of annual plants wash ashore and germinate on the beach, where they survive until a storm washes them away or they reach the end of the growing season.

Dunes

The dunes on a barrier beach are the estuary's primary defense against flooding by storm-driven tides, although a certain amount of this flooding is beneficial. The key to extensive dune

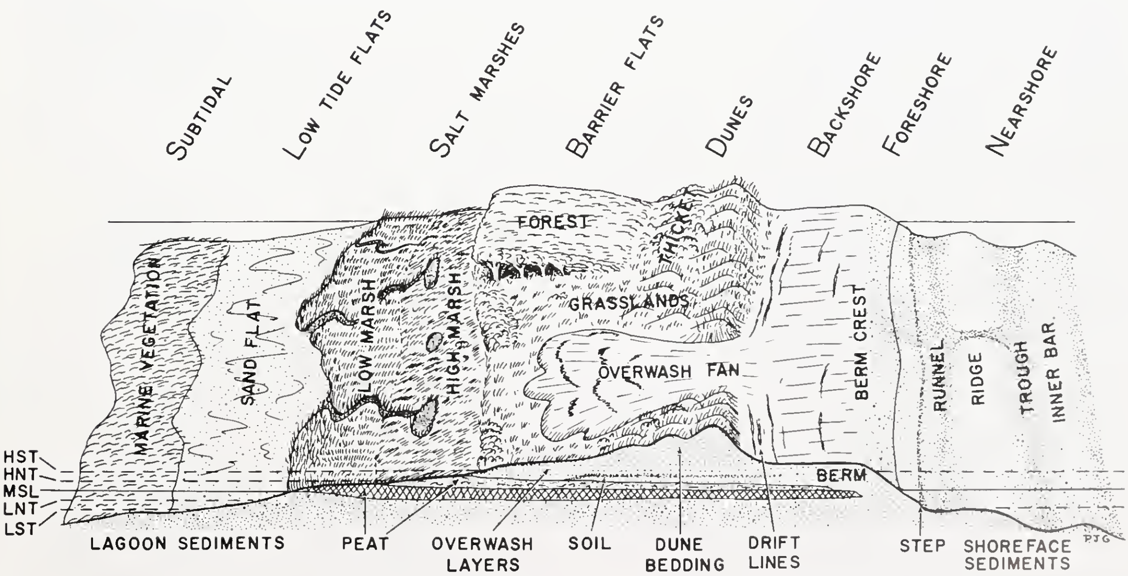


Figure 3. The basic physiographic and ecological zones of a typical barrier beach. The diagram incorporates parts of all barrier beaches, and does not imply that every barrier resembles the drawing. HST = high water of the spring tide; HNT = high neap tide; MSL = mean sea level; LNT = low water neap tide; LST = low water spring tide.

growth is having beaches that lie across prevailing, generally fair weather winds. (Most sand movement occurs during the dry winds of high pressure systems, since sand that is wetted by rain is much harder to move.) On the northern Atlantic seaboard, the best developed dunes are on beaches with northwest, or south and southwest, exposures; on the southern Atlantic coast, big dunes are also found on coasts with northeast exposures. All these exposures face prevailing winds: in the north, they are northwest during winter, southwest in summer; in the south, they are north and northeast during winter, southwest in summer.

Sand blown off the beach would just keep moving inland if it were not for the dune grasses: wild rye (*Elymus*) in the far north, beach grass (*Ammophila*) in the Northeast and Europe, sea oats (*Uniola paniculata*) in the southeastern United States, and other species elsewhere in the world. These grasses have the ability to tolerate salt spray—a major component of the coastal environment—and burial by wind-blown sand. The grasses foster the development of dunes. They grow upward and outward as the blowing sand accumulates around them. Following each increment of burial, the grass grows upward during the next growing season and sends out long, straight runners that produce rows of new plants. As the dune grows and the grass colonizes the sand surface, the dune remains in place and eventually is stabilized by the vegetation. Other species will invade the stabilized dune and add to the vegetative cover. Many of these species are nitrogen fixing plants, such as bayberry and beach pea, that help to support other plants as they add needed nitrates to the barren sand.

With increasing stability and protection from spray, shrub thickets and eventually woodlands develop on the dunes. The zonation patterns are mostly the result of salt spray as are the wind-shaped trees. The salt kills the windward side of the tree, while the leeward side can continue to grow, resulting in a flag-form tree. The rates of vegetation succession, one community replacing another, can be remarkably rapid, in part as a result of the nutrients carried ashore by salt rains from the sea. Too much salt can kill and damage terrestrial plants, yet small quantities that enter the sand with rain act as a fertilizer. The relatively good moisture-retention capacity of dune sand is also a factor in vegetation development.

As dunes build on a growing spit, more and more sand is trapped on the seaward edge of the barrier, and washovers by storm tides are prevented from occurring too often. This relative stability provides time and proper conditions for the development of salt marshes along the bay or lagoon side of the barrier, and these marshes add greatly to the over-all productivity of the barrier/estuary system.

Barrier Flats

Dunes are the major topographic feature of the interior of the barrier beaches of the north and northeast. The barriers of the mid-Atlantic and southeastern coast, however, are more typically broad, low, and flat, with only a reduced dune ridge or zone along the ocean. On natural barriers—those that do not have a man-made dune line—there are numerous passes through the dune fields where storm tides can wash across. The dominant topographic feature on most of these barriers is a flat grassy plain, produced by regular overwash from storms that push sand across the barrier from the ocean beach and dunes. The formation of these flats is tied to the storm floods that can cover most of the barrier and the deposition of sand that occurs during the flood. The process is most common on barrier beaches of the mid-Atlantic and southeastern coasts.

One of the most important species of vegetation on the flats is salt meadow cord grass (*Spartina patens*). When overwashes occur, the new layers of sand are quickly colonized by the grasses growing up through the sediments from below. What sand is not stabilized blows up into low dunes along the ocean side of the barrier. Sand carried back across the barrier by overwash is frequently blown into dunes. With decreasing frequency of overwash, either because of increasing dune growth or lack of storms, barrier flats support thickets, followed in time by woodlands and, finally, forests. The woody vegetation usually starts on the backside of the flat near the salt marsh border and grows toward the dunes as more and more stability develops.

The barrier flat is another place where beach sediments may be deposited before they reach estuarine or other inshore waters, and over which storm waves can spread and lose energy. By the time an overwash flood passes the beach, dunes, and flats, it is usually a thin sheet of water flowing gently into the bay.

Salt Marshes

Fringing the back side of most barrier beaches are intertidal salt marshes that may be regularly or irregularly flooded depending on their elevation. Of greatest interest to students of estuarine productivity are the regularly flooded marshes close to tidal inlets. These are of two types, the low marsh and the high marsh.

The low marsh occupies the intertidal region from approximately mean sea level (lower in the South and higher in the North) to the upper level of the neap tide. This zone is dominated by salt marsh cord grass (*Spartina alterniflora*), the most productive member of the marsh community. It is joined by other species, particularly macroscopic algae on Northern marshes, but none are as significant as *Spartina alterniflora*. The low marsh community can extend well up into the high marsh, or irregularly flooded regions along tidal creeks and depressions where it occupies the banks which still experience regular flooding.

From the neap tide mark to the highest spring tide zone is the high marsh, a community dominated by salt meadow cord grass (*Spartina patens*), along with black rush (*Juncus gerardi*) in the North, needle rush (*Juncus roemerianus*) in the South, salt grass (*Puccinelia maritima*), spike grass (*Distichlis spicata*), and others. This zone is flooded only during spring tides and storms, and is found wherever irregular tidal conditions exist, such as those sections of a barrier far from an active inlet.

Of the two types, the low marsh is the most important contributor to the productivity of the estuary since it is flooded during every tidal cycle. The high levels of productivity in these marshes (on the order of 1 to 2 kilograms per square meter per year dry weight standing crop of *Spartina alterniflora*) help support the estuarine food chain in the lagoon behind the barrier. A good deal of marsh productivity goes into the organic peat deposits that make up the floor of the marsh, and sediment in the water is also trapped by the marsh grass. The end result is that the marsh actually can build itself up out of the optimal tidal range. The most productive salt marshes behind barriers are usually the youngest, those that formed recently in the life of the barrier, or are close to inlets. As the marsh ages, it will lose much of its value to the estuary. One of the interesting features of the barrier beach/lagoon estuarine system is that new marshes can be created by the oceanic processes of overwash and inlet formation that build and change the barriers (Figure 4).

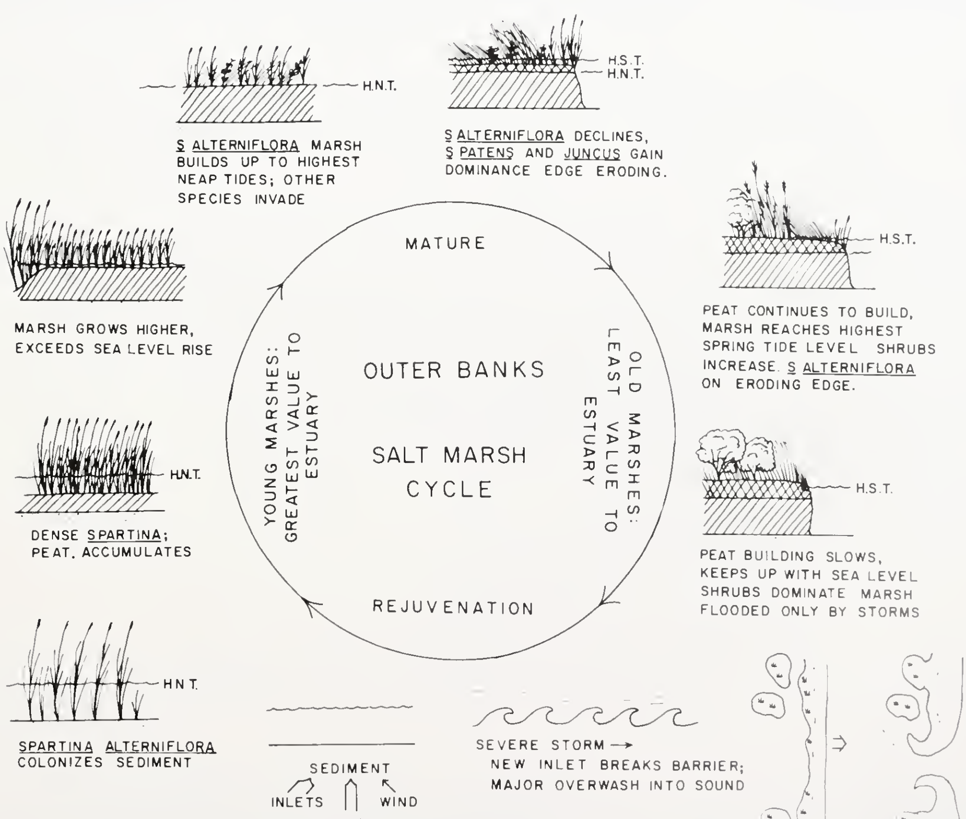


Figure 4. A proposed cycle of salt marsh formation, succession, and redevelopment on a barrier island system, such as the Outer Banks. (After Godfrey and Godfrey)

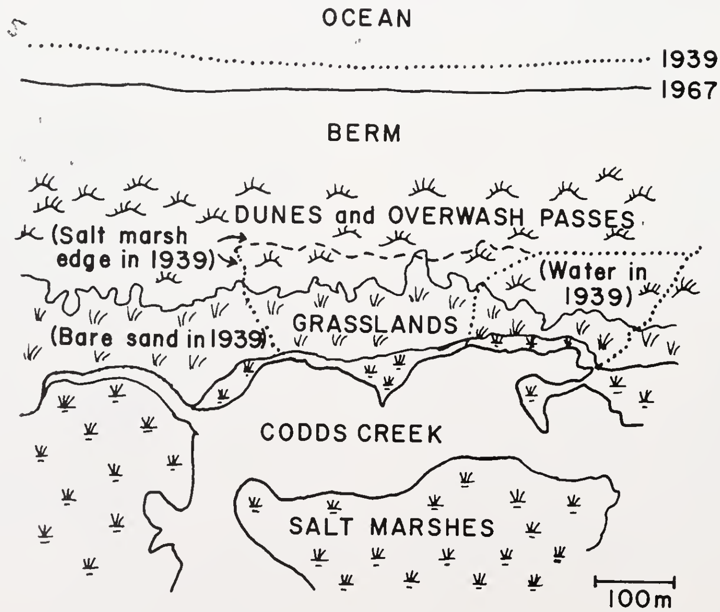


Figure 5. Evidence of overwash retreat on Core Bank, N.C. Figure 5a: Aerial view of the Codds Creek area in April, 1976, showing the berm with scattered dunes, the predominance of overwash fans, barrier flats with grasslands and scattered shrub thickets that grade into the high marsh (light tones), and the low salt marsh (dark tones). Figure 5b: Map of changes at Codds Creek taken from aerial photographs of 1939 and 1967. Overwashes during the late 1950s and early 1960s filled in areas that were once marsh and open water, and portions of the fill became highly productive salt marshes.

Formation of Salt Marshes

Salt marshes can form behind barrier beaches in four ways: invasion of uplands as the sea level rises, sediment buildup from river outflow, overwash, and inlet dynamics. Of these four, the most common processes along most of the East Coast are overwash and inlet dynamics, the latter being most significant in many areas.

If a major overwash moves sand completely across a barrier beach into the lagoon, the sediment dropped into the water will soon be colonized by a new salt marsh. In some cases, older marshes are buried by the sand, but new and often more productive marshes form at the lagoon's edge (Figure 5). As a spit grows, the early stages are dominated by overwashes that regularly move sand from the ocean to the bay. The sand brought in from the beach is colonized by *Spartina* grass and the growing marsh follows the spit. Once dunes start to form, the overwash slows down. This process eventually becomes a relatively rare event until the dunes begin breaking down from retreat of the shoreline. Major overwashes that occur after a barrier system is created move additional sediment to the backside and a fringe of marsh grows into the bay.

Of considerable importance to the barrier/estuary system are the inlets that provide a means for marine organisms to move in and out of the estuary and for organic matter produced in the estuary to move seaward. The inlets also are a sediment trap. Sand moving along the beach is carried into an inlet where it is deposited in large shoals. When the inlet eventually closes, as most temporary storm created inlets do, these shoals, depending on their elevation, become salt marshes or underwater grass beds: these communities thus occupy large areas of formerly open water (Figure 6). A look at marsh islands behind barrier beaches all along the East Coast shows the pattern of flood tide deltas that mark the sites of old inlets. As inlets open and close, the development of new marshes and the erosion of older marshes along the sides of the inlet become part of the mechanism that rejuvenates aging marsh systems behind many barriers.

In some cases, salt marshes are absent from the bay side of the barrier. The reasons for these conditions are unclear but seem related to distance from an inlet, recent overwash, wave conditions, or drastic changes in bay salinity. There is evidence that marshes behind barrier beaches, especially older ones, can be eroded away by continual wave action in a large bay. Such sites of erosion are invariably a long way from existing or

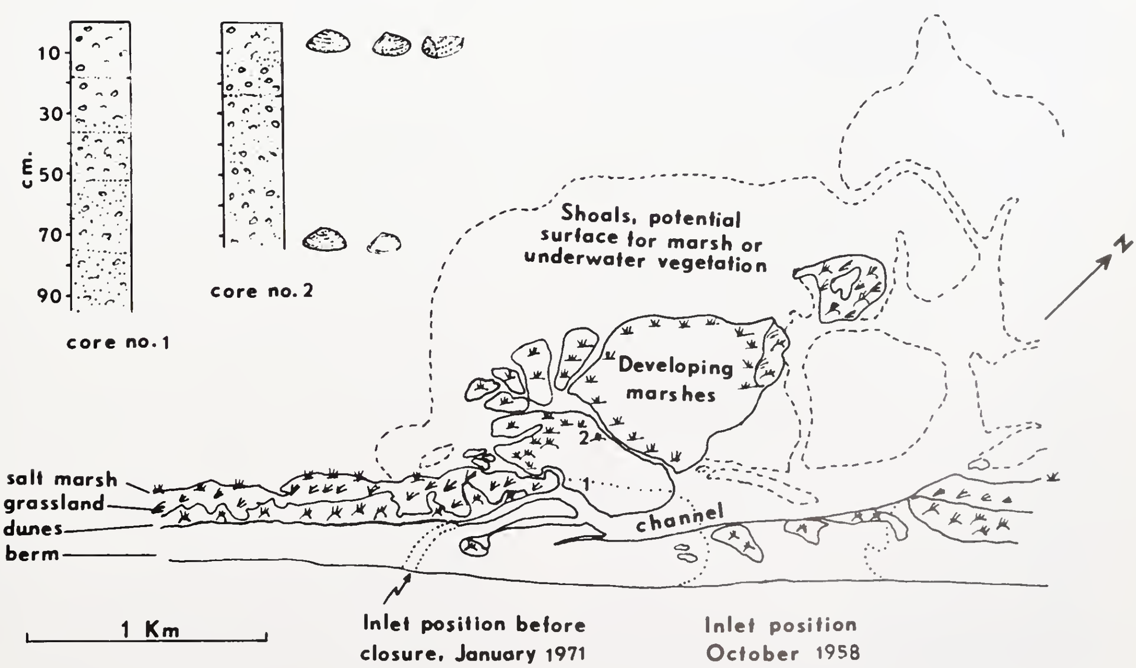


Figure 6. Changes at Drum Inlet, North Carolina, showing formation of new salt marshes on tidal deltas. Cores show the composition of a shoal and the presence of beach shelf from littoral drift into the inlet. (After Godfrey and Godfrey, 1974)

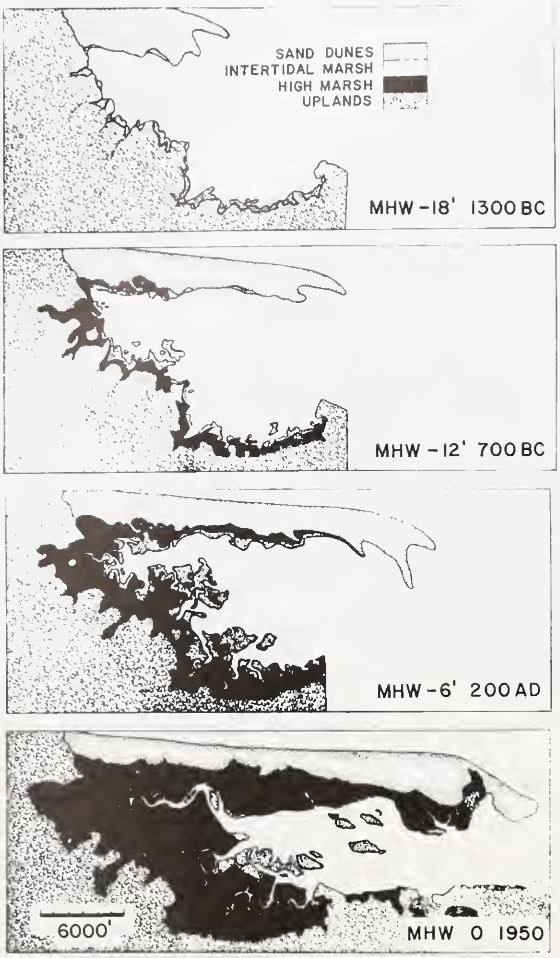


Figure 7. Sandy Neck, Barnstable, Mass., showing the growth of a spit across an open bay with subsequent marsh development behind. If breached by an inlet, such a barrier could become an island.

even recent inlets. Also, sections protected by a major natural or artificial dune system that has stopped overwash often lack marshes on the bay side, or have very old, eroding high marshes. In these cases, excessive protection from inlet formation and overwash is detrimental to the overall estuarine system just as would be too frequent overwashing or inlet formation. Some barrier beaches are so open to wave attack on their back side that marshes cannot develop in the open water and only appear where protected by small barrier beaches attached to the main barrier. Monomoy Island in Massachusetts is a good example of this condition. Some lagoons, such as Laguna Madre behind Padre Island in Texas, develop such high salinities that even the salt tolerant *Spartinas* cannot grow. In all these cases, the back side of the barrier consists of open sand beaches.

Formation of Barrier Beaches

The formation of barriers and the estuaries they protect is the subject of considerable controversy among coastal geologists. The two most commonly discussed theories are the spit theory and the drowned beach ridge theory. A third idea combines the two into a sensible compromise. A fourth relates to the reworking of sediments brought down to the sea by rivers.

The spit method calls for the growth of a long sand finger off a headland of eroding sediments. As the headland erodes, the spit grows across open water, enclosing a lagoon that develops estuarine conditions: Nauset Beach and Sandy Neck on Cape Cod are good examples of spits (Figure 7). The spit keeps growing in the direction of the littoral drift as long as the source of sand holds out and the spit does not strike land on the other side. In some cases, barrier spits have grown completely across a lagoon and cut it off from the sea, although inlets can form periodically and result in some drainage to the ocean. Such completely closed lagoons of often rather fresh water are sometimes called "salt ponds" and are common features on Nantucket and Martha's Vineyard in Massachusetts. When a spit is breached by inlets, it becomes a barrier island or a series of islands. Monomoy Island is a good example of a barrier spit that became a barrier island when breached by an inlet. Fire Island in New York appears to have developed, at least initially, by the growth of a spit from glacial deposits to the east on Long Island. As the shoreline retreats with the rising sea, so, too, do the spits, even though they are being supplied with sand from an eroding source.

According to the second theory (Figure 8), dune ridges formed along the shore 5 to 6000 years ago as a result of erosion of coastal plain and river sediments, during a time when sea level rise had slowed down from a previously rapid climb following the melting of the ice sheets. Evidence suggests that this slower rate of rise has continued to the present (about 0.3 meters per 100 years). Once the dune ridges formed on what was then part of the mainland, the lowlands behind were flooded and became the broad, shallow lagoons that characterize our southeast coast. With the continuously rising sea, the dune ridges were pushed back to their present positions and are still retreating. These dune ridges became the barrier islands we see today, although they have been reworked many times. The evidence to support this theory comes from sediments beneath the lagoons, which are like mainland deposits rather than marine (as they would be behind spits that grew across open water) and from

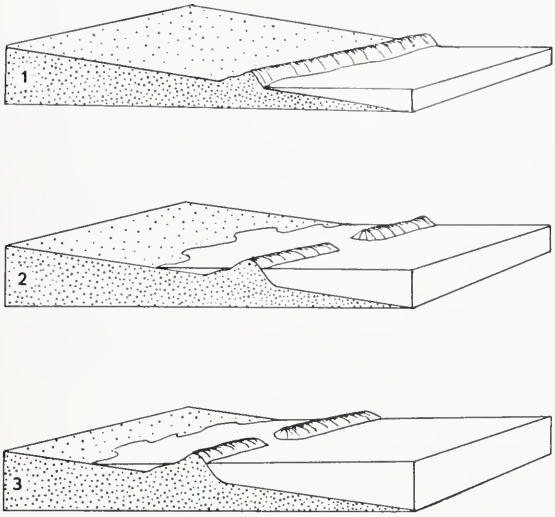


Figure 8. The drowned beach ridge theory of barrier island formation. In stage 1, approximately 6 to 5000 years ago when the sea level was lower than today, beach ridges formed along the coastal plain shore. In stage 2, sea-level rise submerged the ridge, broke through, and flooded the mainland behind creating shallow lagoons. By stage 3, the barrier beaches were pushed further landward and more of the mainland flooded as sea level continued to rise. (Adapted from Hoyt, 1967)

the reworking of old coastal plain deposits that are now offshore. No new sources, such as the eroding glacial headlands of the North, are available on the southeast coast. The Sea Islands off South Carolina and Georgia are actually portions of the mainland that have been isolated as a result of sea level rise. These barrier islands consist of a Holocene beach that is "welded" onto a Pleistocene land form cut off from the mainland by submergence. Overwash and inlet dynamics are not so applicable to these barriers: they can be thought of as a third category of barrier beach. However, it is possible that those barriers experiencing overwash and frequent inlet formation, such as the Outer Banks of North Carolina, were once sea islands that have been reworked several times by the rising sea. Such barriers may be the final stages of a retreating shoreline that has consumed and moved back earlier land forms.

Different conditions exist even in one coastal area, making a combined causal process seem probable. Both the spit and submergence theories are appropriate for various sections of the coast. The fourth mechanism relates to the heavy sediment discharges of major river systems, such as those along the West Coast, the Mississippi River, the Nile, and other large rivers of the world. Where the river empties into the sea, provided the sediments are not trapped by dams upstream, barrier beaches can form as the waves and wind rework the shoals and bars that form in the river delta. They then create beaches, overwash flats, and dunes. When the sands and silts are caught by dams, the barriers begin to erode. This is now happening at the mouth of the Nile and at the mouths of certain larger rivers on the West Coast.

Retreat of Barrier Beaches

The continuing rise of sea level throughout the world—except for the Arctic where isostatic rebound has resulted in a falling sea level relative to the land—will have a major effect on barrier beaches and the estuaries behind them. Along the East Coast, the relative rise, a combination of isostatic decline and eustatic increase, has averaged, as mentioned before, about 0.3 meters a century. Since most of the East Coast is only a few meters above sea level to begin with, the retreat of the shoreline is an important event. From all available evidence, it is clear that the East Coast shoreline is retreating as sea level rises. Most people call this "erosion." It is more accurate to talk of "retreat" where barrier beaches are involved because these structures are capable of landward migration as ecological units. As they retreat, older parts of the estuarine system directly behind the barrier are buried and new marshes created elsewhere. Evidence of complete turnover of barrier beaches onto older marshes comes from coring samples taken on barriers that invariably show marsh peat underneath the dunes. Salt marsh peat is also frequently exposed at low tide on the ocean side of barriers, providing further proof that the barrier beach retreated over old marshes.

The barrier beaches that are undergoing active retreat actually "roll over" themselves into the lagoon or bay behind. A complete turnover of a barrier island, such as Core Banks in North Carolina, can occur within a century. The actual turnover rate depends on many factors, but it is not uncommon to find outcrops of salt marsh peat on the ocean beaches of most East Coast barriers that are only a few hundred years old. The physiographic changes due to overwash are most rapid where wave energy and storm frequency are high, tide range is small, and dune building is minimal.

On southern barriers, overwashed surfaces are quickly revegetated as salt meadow cord grass (*Spartina patens*) pushes up through the new sand. Dune building is subsequently less significant because the sand is effectively stabilized. In the North, however, the cord grass lacks this ability. Instead, dunes are formed on the overwash surface by dune plants that grow from fragments in drift lines. These contrasting processes may help account for the difference in appearance between northern and southern barriers undergoing active retreat.

Inlets are another major way by that barriers retreat. When a particular barrier beach becomes very narrow, by lack of overwash or excessive dune erosion combined with erosion on the bay side, a new inlet is likely to form during a severe storm. When this happens, large quantities of sand are carried into the inlet and well back into the bay or lagoon. As the inlet migrates in the direction of the littoral drift, older marshes may be eroded. When the inlet is finally choked with sand, it closes and new marshes form in what was once open water. The net result is that the barrier system has retreated, often by a considerable amount, with the ecological units retained (Figure 9).

Wind-driven dunes are also a factor in the retreat of some barriers, especially if the wind blows sand across the barrier following storm damage to formerly stable dunes. In some cases, migrating dunes can cover existing marshes and move into the bay behind where waves will spread the sand around. The combination of wind-driven dunes, overwash, and a growing spit on one end of a barrier island can result in a structure that literally migrates in one direction and retreats in another.

These various mechanisms of retreat all have one important consequence: sand is pushed into the bay or lagoon over older marshes, continually raising the base level of the barrier and the estuary bottom. This has the effect of maintaining shallow water conditions even as sea level keeps rising. The barrier beaches and the estuary will not be totally submerged as long as they can retreat. If the retreat is too fast, then excessive filling of the estuary and rapid destruction of the marshes will result. If the retreat is not fast enough, or if sediment transport is hindered by stabilization or development, then the marshes and the barrier system could be submerged in place. The key to survival is a slow, gradual retreat to which all ecosystems involved can react within their intrinsic capacities to recover from the effects of shoreline retreat.

Variations of East Coast Barriers

With the wide latitudinal range and the wide variations of oceanic and shoreline conditions, distinct differences occur along the East Coast between the structure of barrier beaches (Figure 10). The Sea Islands of Georgia are quite unlike the Outer Banks of North Carolina, while the Banks are different from the beaches of Massachusetts. Along our northeastern coast, barriers are rather narrow and are covered with dune fields that support grassland and thickets with dune ridges close to the beach. On the Outer Banks, the natural barriers are mostly wide, low, flat, and grassy, with low scattered dunes some distance from the beach. A few places have high dunes that support well-developed forests. On the Sea Islands of Georgia, the dunes are continuous and the beach often narrow and covered with plants. The dune line is well developed. The land behind the dunes is mostly covered with dense

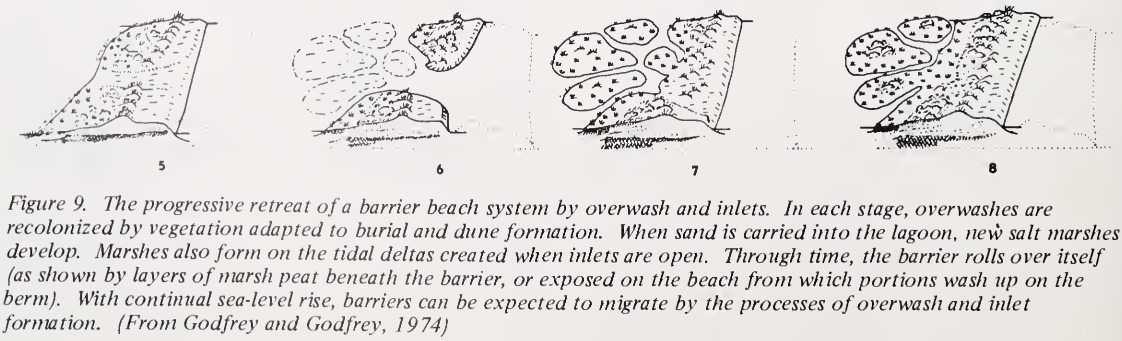


Figure 9. The progressive retreat of a barrier beach system by overwash and inlets. In each stage, overwashes are recolonized by vegetation adapted to burial and dune formation. When sand is carried into the lagoon, new salt marshes develop. Marshes also form on the tidal deltas created when inlets are open. Through time, the barrier rolls over itself (as shown by layers of marsh peat beneath the barrier, or exposed on the beach from which portions wash up on the berm). With continual sea-level rise, barriers can be expected to migrate by the processes of overwash and inlet formation. (From Godfrey and Godfrey, 1974)

oak forests. On our Gulf Coast, the barriers are more like the Outer Banks, except that they have low dunes near the beach. There are grasslands on most of the barriers, and pine forests on others. Generally speaking, each barrier beach area worldwide has its own particular characteristics.

Threats to Barrier Beaches

For many years, coastal interests were convinced that erosion was the number one destructive force on barrier beaches. Much effort was spent in stabilizing the coastline with dunes and dikes, sea walls, groins and jetties, and other structures. Yet recent research has shown us that barrier beaches can survive erosion and sea level rise quite well—after all, these systems evolved in response to oceanic forces. The real threat to the barrier beach/estuary system is modern development: the damage wrought by man can be mammoth and irreversible. During the last decade in particular, the rapid development on the East Coast of second homes, condominiums, hotels, apartments, new cities, roads, and marinas has far exceeded the relatively minor damage done by centuries of grazing and localized land-use activities, which were once accused of causing massive destruction of barrier beaches (Figure 11).

Only relatively inaccessible areas or large blocks of land protected by public or private ownership have escaped development and urbanization. Elsewhere, structures have been erected close to the beach, completely oblivious to the facts of sea level rise, storms, flooding, erosion, and shoreline retreat. Vast sums of money have been spent in vain attempts to stop the barrier system retreat, yet few people learn from the consequences. And while the barrier beaches are being developed, the estuaries are dredged and filled for boat basins or further construction. In many areas, erosion of both the ocean side and the bay side of barrier beaches is a severe problem. Groins and jetties are used to stop sand movement but they can create as many problems as they solve. Where major construction has been undertaken, overwash and inlet development has been stopped and all natural means by which the islands survive sea level rise hindered.

Some federal agencies have been building dikes and dune lines up and down the East Coast with questionable promise of stopping erosion or preventing storm damage. The dikes can slow things down for a while, but they also foster a false sense of security that encourages further development. Dunes are part of the natural environment and play

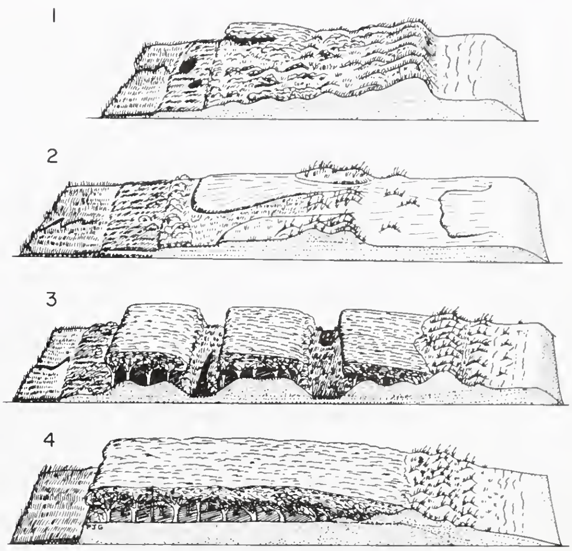


Figure 10. Typical barrier beaches found along the East Coast. 1: A Northeast coast barrier where dune building is more significant than overwash. Well-developed dune lines exist close to the beach, and are often scarped if the beach is retreating. The barrier is made up of dunes on top of earlier overwash deposits. It is vegetated by dune grasses, shrubs, and woodlands where enough protection exists. 2: A Central and Southeast coast overwash barrier. Regular overwashes create a broad, gradually sloping barrier that is made up primarily of overwash strata and terraces with dunes scattered on top. The barriers are basically flat, covered with grasslands and scattered thickets toward the backside, and extensive salt marshes behind. 3: An East Coast accreting barrier, or one that is relatively stable, having been built originally as dunes formed on a growing beach. The uplands are forest and interdune lowlands are pond, marsh, or swamp. Woodlands occur just behind the main barrier dune and are "pruned" by salt spray. 4: The "Sea Island" type of Southeast coast barrier. These are drowned sections of the mainland, with a modern beach attached. The vegetation is dominated by forest, usually right up to the main dune ridge. Such barriers are common where sea energy is low, and tide range wide.

an important role in the barrier beach structure, but they cannot stop the inevitable retreat where such conditions now exist. Many engineering plans for building seaward dunes involve dredging estuaries to get the needed sand. While some organizations are aware of the futility of such operations in the long run, stabilization projects are still being promoted, often with strong backing by an uninformed public or by developers anxious to make private gain at government expense. A recent example is Fire Island in New York, where a plan to "stabilize" the whole island with a 6-meter-high dike the length of the island is being promoted by the U.S. Army Corps of Engineers.

Figure 11. The effects of barrier beach retreat by storm driven overwash on developments at Buxton, N.C.

Figure 11a: Motels that were built directly behind a man-made barrier dune as they appeared in 1969.

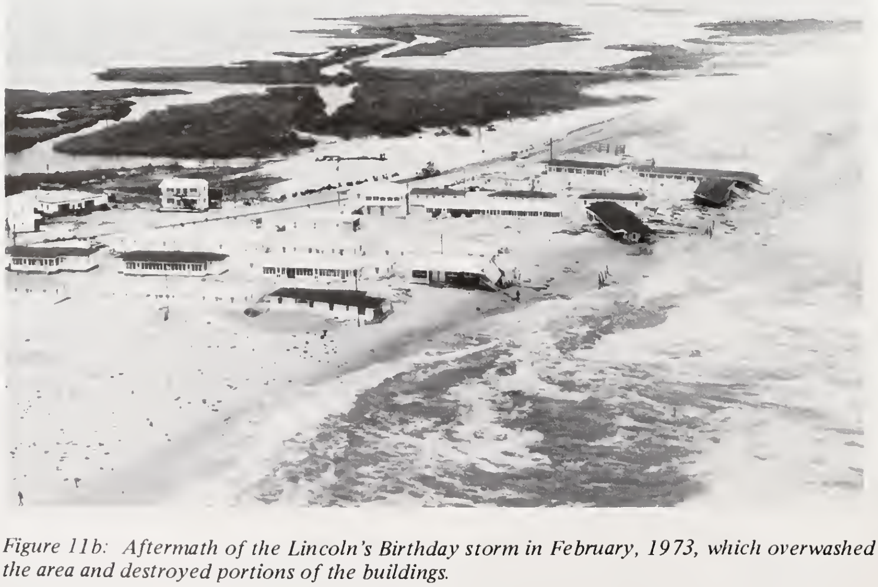


Figure 11b: Aftermath of the Lincoln's Birthday storm in February, 1973, which overwashed the area and destroyed portions of the buildings.

There is mounting evidence that the major development projects on the East Coast have grown up during a rather unusual lull in storm activity, with most hurricanes going off into the Gulf of Mexico. The storm cycle may now bring the Atlantic hurricane back to its more typical track up the Eastern seaboard, as was common during the 1950s and early 1960s. The cost in dollars and lives will be staggering when the next Camille-size hurricane sweeps up the Atlantic coast. Were it not for recent private and public efforts, many more miles of barrier beach and estuary would be claimed by developers.

Once barrier beaches are developed, they face not only the obvious threat of storm damage, but they lead to other, unforeseen problems. In particular, the effect on the fresh water table is becoming a major environmental problem as more and more people draw water from that source. Nearly all coastal developments are dependent on wells in the fresh water lens, and the volume in that lens will decrease if the withdrawal rate exceeds the precipitation input, the only source. Already, many coastal communities on barrier beaches are suffering salt water intrusion into their wells. Compounding the problem, at least from a public health point of view, is that septic tanks and leach fields put human wastes back into the fresh water lens where the water can be recycled by another consumer in short order. Pumping the wastes out to sea will only aggravate the total water budget problem in the lens. The water budget on a barrier beach is critical to the survival of ecosystems on that barrier and should be a major limiting factor to development.

Conservation Programs

The strongest force in preserving barrier beaches and associated estuaries has been the public demand, through Congress, for coastal parks and wildlife refuges administered by the Department of the Interior. The National Park Service now manages and protects some of the most outstanding barrier beaches along the East Coast: Fire Island on the south shore of Long Island, New York; Assateague Island, Maryland-Virginia; Cape Hatteras and Cape Lookout in North Carolina; Cumberland Island, Georgia; Canaveral, Florida; Gulf Islands, Florida-Mississippi; and Padre Island, Texas. Barrier beaches also can be found in Acadia National Park in Maine, Cape Cod National Seashore in Massachusetts, Gateway National Recreation Area near New York City, Olympic National Park in Washington, and Point Reyes National Seashore in California. The National Park Service is developing management plans for these beaches based on the scientific knowledge of what barriers are doing.

The Fish and Wildlife Service manages numerous barrier beach systems as well, including the Parker River Wildlife Refuge on Plum Island and the Monomoy Island Wilderness Area in Massachusetts; Chincoteague and Back Bay Refuges, Virginia; Peal Island, North Carolina; Cape Romain, South Carolina; Wolf, Blackbeard, and Wassaw Islands, Georgia; St. Vincent Island, Florida; and Chandeleur Island and associated areas, Louisiana. Nearly every coastal state has parks on barrier beaches. Coastal Zone Management funds administered through the states are a new force in controlling the development of barrier beaches. State laws enacted to protect wetlands and beaches are now being tested by developers: for example, an important court test is coming up between developers and the state of Massachusetts, in which the state has used its authority under its present Wetlands Act to prevent development of an eroding dune system on a Nantucket barrier beach.

Among private agencies, the Nature Conservancy has led the way by purchasing an outstanding chain of barrier beaches, the Virginia Coast Reserve, which is the last undeveloped system of its kind on the East Coast. This acquisition stretches some 50 miles from Metomkin to Smith Island, Virginia. In Massachusetts, another private conservation organization, The Trustees of Reservations, has been purchasing outstanding barrier beaches around the state, including Cranes Beach, and several areas on Nantucket, Martha's Vineyard, and Chappaquidick Island.

The Conservation Foundation and the Environmental Defense Fund have developed new programs in recent years for promoting the conservation of barrier beaches. For example, the Conservation Foundation organized a two-day workshop in May of 1976 on barrier islands, sponsored by 25 conservation organizations. The workshop brought together coastal scientists, conservation groups, government agencies, and lay people interested in developing a program that would promote barrier island preservation. The Conservation Foundation, along with the Open Space Institute and Natural Resources Defense Council, supported a series of inventories that determined the current status of barrier beaches and islands all along the East Coast. As a result of the Barrier Island Workshop, a steering committee was created to formulate and carry out an action plan that will focus attention on barrier beach threats. In addition, the Environmental Defense Fund is preparing a comprehensive bibliography of barrier island technical literature that will be made available to the public.

All of this activity, and much more, is directed at preventing the loss of barrier beaches to unwise development. One hopes that it is not too late to protect what remains of the barrier beach/ estuary systems of this country and elsewhere. For only man can really destroy the barrier beach.

Acknowledgements

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All photographs and illustrations are by the author unless otherwise noted.

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Nutrients in Estuaries

by John E. Hobbie

The abundant animal life of estuaries depends on the phytoplankton, marsh grasses, and submerged plants for most of its food. All of these plants require a continual supply of nutrients for rapid growth. Because seawater is rich in many of the nutrients plants need, such as potassium, calcium, and magnesium, only phosphorus (P) and nitrogen (N) are so low in concentration that they control the growth of estuarine plants. For this reason, most of the research on nutrients in estuaries has dealt with these two elements.

Sources of Nutrients

An estuary must have a continual supply of nitrogen and phosphorus to maintain its high rates of photosynthetic production. This supply comes from three sources: land runoff, sediments, and seawater that moves upstream. All three sources are always present, but the relative importance varies from estuary to estuary. Thus, there is a continuum of types that ranges from the clear estuaries such as Port Charlotte on the west coast of Florida to the very turbid estuaries such as those behind the barrier islands of Georgia. In the turbid estuaries there is a great deal of sediment in suspension and a corresponding high rate of exchange of nutrients between the sediments and water. Clear estuaries, in contrast, have very little sediment-water interaction.

There are few nutrients in rivers draining undisturbed forest lands. In a New Hampshire forest, for example, more nitrogen and phosphorus fall in the rain than leave the forest in streams. Forests retain these nutrients even though large amounts may cycle through the soil and vegetation each year. In the same forest, 1900 grams of phosphorus per hectare reach the forest floor as leaf fall, but only 21 grams of phosphorus per hectare leave in streams. In contrast, streams draining farmland and urban areas transport eight to ten times more phosphorus than the average for forests (Table 1), and the nitrogen follows the same pattern. This high rate of transport occurs in most of the streams feeding estuaries along the East Coast of the United States.

The sediments of most estuaries contain enormous amounts of nutrients. In some cases, these sediments were laid down in shallow marine waters; in other cases, the sediments come largely from the feeder rivers and from organic matter produced in the estuary. It is believed that most of the phosphorus that fertilizes the turbid marshes and estuaries of Georgia arises in an exchange from the clay sediments to the water.

A few estuaries receive most of their nutrients from ocean water. One of these, the Ythan in Scotland, receives 70 percent of the phosphorus and 30 percent of the nitrogen from inflowing seawater.

Table 1. Amounts of nitrogen and phosphorus (kilograms/hectare/year) in runoff from an average area (after Vollenweider, 1968). The range for farmlands and meadows and grassland reflects differing amounts of fertilizer reaching the streams.

Source	N (kg/ha/yr)	P (kg/ha/yr)
Sewage		
Human wastes	6.6	0.8
Detergents		0.4
Street runoff	0.7	0.1
Industrial wastes	0.7	0.1
	8.0	1.4
Agricultural and forest runoff		
Arable land	2.3-5.8	0.1-0.5
Meadows and grasslands	4.3-13.3	0.1-0.5
Forests	1.0	0.1
	8.6-20.1	0.3-1.1
Total	16.6-28.1	1.7-2.5

Changes During Transport to Estuary

As soon as nutrients enter a stream or river, they begin to be changed. Ammonia and phosphate, for example, may be adsorbed by sediments or by inorganic particles in the water, while these two, plus nitrate, may be taken up by algae. There are also processes that reverse these trends, so nutrients are released during decomposition of the algae; some of these nutrients may move from particles back to the water if the concentration in the water drops too low. Overall, the net movement is from the dissolved into the particulate forms. Some of the particulate matter may eventually reach the estuary, but much of it is trapped in the sediments of the rivers or in reservoirs. In the upper Potomac Basin, for example, 38 percent of the phosphorus entering the streams is retained in the channel.

Nitrogen is also changed within streams both by action of organisms and by adsorption into sediment. Ammonia adsorbs readily, so most of the nitrogen leaving farmland or forest is in the form of nitrate. However, in streams or rivers where sewage contributes nitrogen, this is mostly as ammonia and is rapidly oxidized to nitrate (Figure 1). Overall, there is a net loss of inorganic nitrogen from river waters. Unfortunately, no study has been detailed enough to include the dissolved organic nitrogen. Yet enough has been done so that we know that the organic nitrogen is the predominant form. Until the nitrogen budget of a river is determined, we will not know whether the missing nitrogen is lost as N_2 gas, is permanently trapped in the sediments, or is transported as organic nitrogen.

Changes Within an Estuary

Physical and Chemical Processes

In most estuaries, the inflowing seawater has a much lower concentration of nutrients than the entering fresh water. Therefore, if the dilution of the

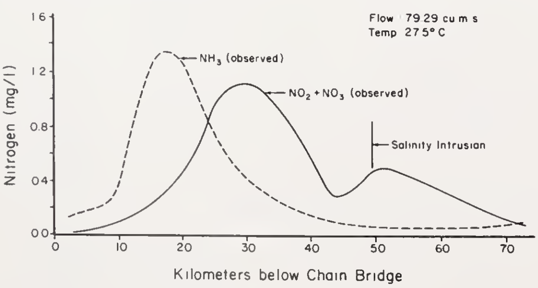

Figure 1. The average concentrations of ammonia (NH_3) and nitrite plus nitrate ($NO_2 + NO_3$) in the Potomac River from 17 to 22 August 1968. The brackish water begins at about 50 kilometers. (After Jaworski et al., 1972)

nutrient-rich fresh water by the seawater were the only process affecting nutrient concentration, then nutrients should decrease in direct proportion to the increase in salt concentration. Usually other processes are acting in addition to dilution, but in Charlotte Harbor, on the west coast of Florida, dilution predominates. As seen in Figure 2, the decrease in concentration of phosphorus closely follows the ideal dilution curve, indicating that neither biological nor chemical processes are important. This comes about because the Peace

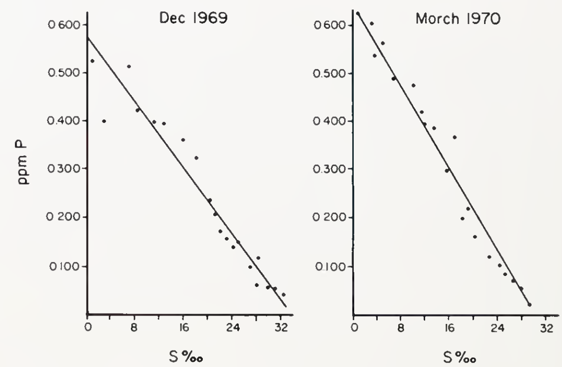

Figure 2. Phosphorus concentrations and salinity in Charlotte Harbor, Florida. An ideal dilution curve is given as a solid line, while actual measurements are plotted as dots. (After Alberts et al., 1970)

River receives phosphate from mines; by the time it enters the estuary it contains 20 microgram atoms of phosphorus per liter. However, there is not enough nitrogen in the estuary to allow algal blooms to develop and take up this phosphorus. The interaction of nutrients, especially phosphorus and ammonium, with sediments and particulate matter is another important process. This may be adsorption to silt and clay, or it may be a more complex chemical reaction. Phosphorus, for example, may be bound to particulate matter as a part of a phosphorus-iron-solids complex. Whatever the exact nature of the process, it can be rapid; in one experiment with water and stirred estuarine sediment, half of the phosphorus present in the water became attached to the particulate matter within 15 seconds.

The load of particulate matter and its adsorbed nutrients is large in a flowing river. When the current decreases as the river broadens into the estuary, much of the particulate matter sinks to the bottom. This sediment is very rich in nutrients (Figure 3, sediments above the seven-mile sample). Actually, some of the particulate matter is colloidal, that is, is made up of very small particles with an electrical charge. The charges on the

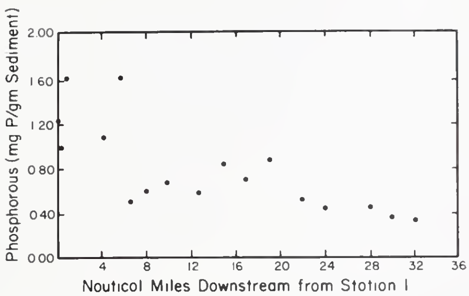

Figure 3. The amount of phosphorus extracted from sediments by acid treatment (available phosphorus) as a function of distance downstream from the fresh water end of the Pamlico River Estuary. (After Upchurch et al., 1974)

particles keep other particles away, so there is no aggregation. When the particles move into brackish water, the ions may neutralize the charges, and the large particles and flocs that are formed rapidly sink. This coagulation is difficult to demonstrate in nature as both organic and clay mineral colloids may be present and the adsorption sites may be filled with a variety of organic and inorganic ions (Edzwald et al., 1974). In addition, other processes may obscure the coagulation effects. Thus, in the estuary illustrated in Figure 3, the large populations of clams (*Rangia cuneata*) in the upper estuary may be just as effective in removing particulate matter from suspension as is the process of coagulation.

No matter what the exact mechanism may be, large amounts of nutrients are deposited in estuarine sediments. For example, in the waters of upper Chesapeake Bay where the average water depth is 10 meters, an annual loss of 150 milligram atoms of nitrate per square meter was measured during the late spring and summer (Carpenter et al., 1969). This amount of nitrogen is contained in 1 millimeter of sediment per square meter; although the annual sedimentation rate is difficult to measure, 1 millimeter per year is a reasonable rate.

Once nutrients are deposited in the sediments, they are not necessarily lost forever. Phosphorus will move from the particles back into the overlying water or into the water within the sediment (interstitial water). This occurs when the concentration of phosphorus is low in the water (Table 2). In this experiment, the sediments released phosphorus to the water when the concentration fell below 0.9 microgram atom of phorphorus per liter. The sediments in this way act as a giant reservoir of phosphorus. In nature, the nutrient-rich interstitial water may be moved out of the sediments by the movements of animals living there. Tidal movements may also resuspend sediments in the water column so that the exchange between the sediment and the water is facilitated.

In certain estuaries large amounts of fresh water move towards the sea on top of a layer of seawater moving upstream. Mixing does occur, but it is gradual. When organisms or particles sink or actively move into the bottom waters, they are moved upstream. Nutrients that come into solution in the bottom waters, either through decomposition of organisms or by exchange from the sediments, are also moved upstream. In this way, the estuary acts as a nutrient trap and holds the nutrients that would otherwise be quickly flushed out to sea. The Gulf of Venezuela is a good example of this countercirculation (Figure 4). Here, the seawater with 0.5 microgram atom of phosphorus per liter moves into the shallow waters of the Gulf. As it does so, it accumulates another 0.5 microgram atom of phosphorus per liter. In Chesapeake Bay, large numbers of the dinoflagellate *Prorocentrum* are moved upstream by this type of trap. However, the Georgia estuaries do not show this mechanism.

Biological Processes

Removal of particulate matter from suspension by organisms is called biodeposition. This process is

Table 2. Influence of suspended sediments on estuarine water of varying phosphate content. Final phosphate values are mean ± one standard error of the mean (n). Phosphate in micromoles/liter, 5 March 1964. (After Pomeroy et al., 1965)

Initial PO_4^{3-} of water	Final PO_4^{3-} of water	PO_4^{3-} in sediment (g PO_4^{3-}/g dry sediment)	n
0	0.72 ± 0.03	−1.0	7
0.5	0.73 ± 0.02	−0.4	4
1.0	0.90 ± 0.07	+0.6	8
2.5	0.89 ± 0.05	+7.6	8
4.3	0.87 ± 0.002	+11.0	8
8.4	1.61 ± 0.22	+30.9	3

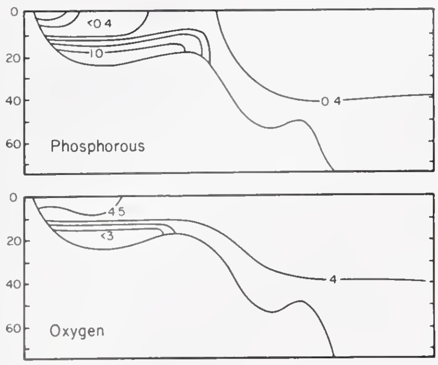

Figure 4. The distribution of total phosphorus and oxygen in a section along the axis of the Gulf of Venezuela (the depth is in meters). (After Redfield et al., 1963)

poorly understood but has the potential of being much more important than the physical-chemical processes. One way this process operates is by the filtering action of molluscs, such as clams and oysters. These can filter clay particles from the water and produce pellets and flakes that then behave like sand grains. Other particulate matter, and its associated nutrients, is also removed at such a rapid rate that an oyster bed can completely cover itself with deposited sediment in 36 days. This is eight times the amount of sediment deposited by gravity alone. Oysters filter a surprisingly large quantity of water each week; estimates vary from 70 to 300 liters. Clearly oysters and other filter feeders in estuaries can completely process the whole volume of the estuary in a few days or weeks.

Another biodeposition process is the trapping of particulate matter by large rooted plants. Mangroves provide protection from wind and currents so that particles rapidly settle out. Marshes also act as giant filters of particulate matter both mechanically and as sites for many filter feeders (for example, mussels). In addition, the marsh vegetation stabilizes the sediments so that they are not resuspended at every tidal change (Odum, 1970). The importance of this process is hard to gauge, but it is known that the onset of severe silting of many English harbors coincided with the filling and diking of the marshes.

Large amounts of nutrients are taken up by the photosynthetic organisms of estuaries such as the rooted plants, the attached algae, the phytoplankton algae, and the sediment algae. The most easily seen of these are the large plants such as the salt marsh grass *Spartina* and the eelgrass *Zostera.* These plants take up nutrients only from the sediments and thus do not compete with the algae directly. However, they do create conditions favorable for biodeposition and also tie up a tremendous amount of nutrients in the plant tissue. Thus, the annual production by *Spartina* of 700 grams of carbon per square meter in a Georgia salt marsh will incorporate 11 grams of nitrogen per square meter and 2 grams of phosphorus. The underground roots and rhizomes may contain twice this amount. Other estuaries, such as that near Beaufort, North Carolina (Table 3), will have the submerged plants as the main producer (here it is eelgrass).

Phytoplankton algae are not abundant in many estuaries because of rapid flushing and the turbid waters. Yet they may be the most important food for zooplankton and invertebrate larvae. In very large estuaries, such as Chesapeake Bay, there is adequate time for these algae to develop, and annual primary production may reach several hundreds of grams of carbon per square meter.

All the algae in an estuary are extremely effective in removing nutrients, even from nutrient-poor water. Their main competitors may well be the bacteria, which need to remove both nitrogen and phosphorus from the water in order to decompose organic matter from higher plants. In one experiment (Thayer, 1974), where bacteria and algae competed for nutrients in the presence of chopped *Spartina,* the bacteria won and prevented algal growth. Another test (W. G. Harrison, personal communication) showed that most of the phosphorus was taken up by organisms, likely bacteria, that passed through a 1 micron filter. Nitrate and ammonia, on the other hand, were taken up mostly by larger organisms.

Nutrient Cycling

A molecule of nitrogen or phosphorus may pass through organisms and back into a pool of inorganic ions a number of times before leaving the estuary.

Table 3. Organic carbon production (grams of carbon per square meter per year) in salt marshes and adjacent estuaries at Sapelo Island, Georgia, and near Beaufort, North Carolina. (After Cooper, 1974; Williams, 1973)

	Georgia salt marsh ($g\ c/m^2/yr$)	Beaufort shallow estuary ($g\ c/m^2/yr$)
Salt marsh	700	256
Submerged plants	---	300
Attached micro algae	---	75
Mud algae	420	---
Phytoplankton	---	66

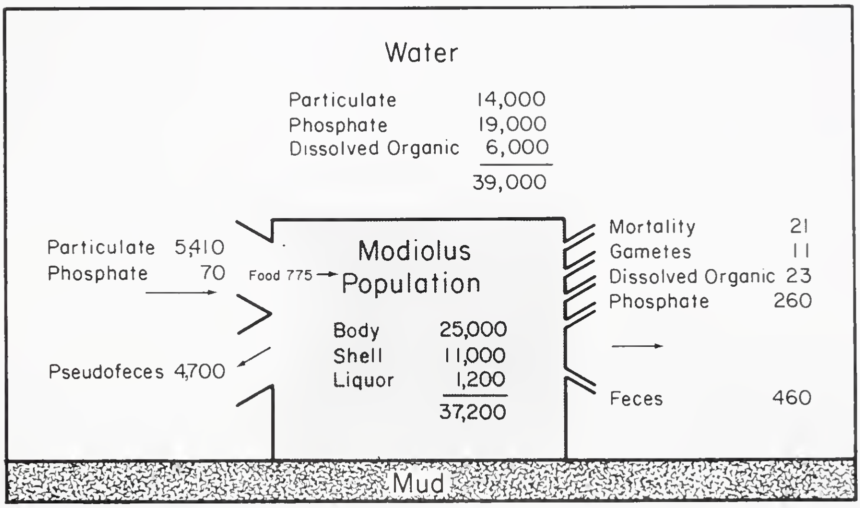

Figure 5. Diagram of phosphorus flow through the mussel population. Values for the water and the mussel population are in micrograms of phosphorus per square meter per day. The flux rates of phosphorus in food and pseudofeces are calculated values necessary to balance the other, measured flux rates. (After Kuenzler, 1961)

This cycling may actually control the rate of primary production to a greater extent than the absolute concentrations of nitrogen or phosphorus. A detailed study of the quantity and movement of phosphorus through a population of mussels (*Modiolus*) in a salt marsh (Figure 5) revealed that the animals actually cycled as much phosphorus as did the plants. The mass of the mussels, however, was miniscule compared to that of the plants. The major ecological importance of the mussels in the nutrient cycle was to remove large amounts of particulate matter from the water and to deposit most of this on the marsh surface as pseudofeces.

Plants with roots appear to take up nutrients from the sediments and release some of them to the water. The movements of phosphorus within *Zostera,* illustrated in Figure 6, are complex, and phosphorus appears to move in all possible directions. Much of the phosphorus that is taken into the plant by the roots is lost from the leaves. This "phosphorus pump" can provide all of the phosphorus needed by the phytoplankton in relatively shallow estuaries.

Nitrogen also cycles in estuaries, but we know only a few details. In part, this is a result of a lack of a suitable tool—there is no usable radioactive isotope of nitrogen. The over-all picture is a decrease in the inorganic forms of nitrogen

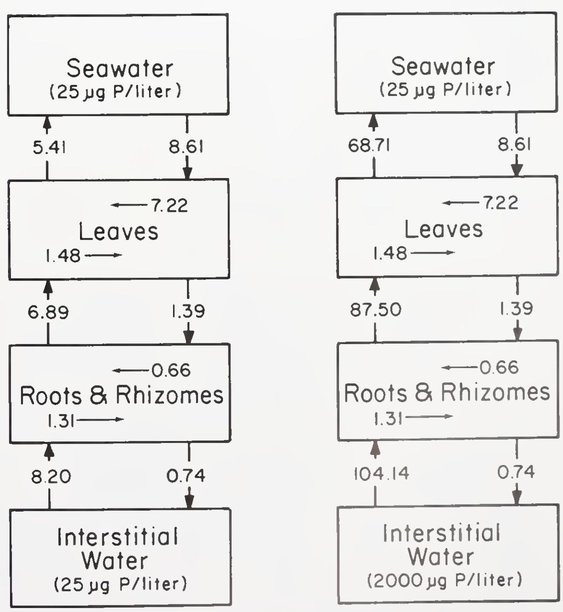

Figure 6. Calculated daily phosphorus flux through 1 gram dry weight of eelgrass. Left: Uniform dissolved reactive phosphorus concentration in water. Right: Phosphate gradient similar to the natural environment. Units are in micrograms of phosphorus per gram of plant per day. (After McRoy et al., 1972)

as the water moves through the estuary (Table 4); this is similar to the events in the river. Nitrate is almost completely removed from solution, while ammonia recycles rapidly. In the Pamlico River Estuary, the urea (another product of decomposition) is completely turned over every day during the summer, but during the winter the turnover time is 200 days. Ammonia in the same estuary may cycle even faster since the algal photosynthesis during a single day in August required 231 metric tons of nitrogen while only 5 metric tons of nitrate nitrogen and 100 metric tons of ammonia nitrogen were present. This implies that ammonia may have a turnover time of half a day.

Table 4. Total inputs and outputs of nutrients as N or P to the Pamlico River, August 1971, through July 1972, in tonnes. (After Hobbie et al., 1975)

	PO_4	NO_3	NH_4
Input	715	2804	795
Output	459	1425	744
Net gain to estuary	+256	+1379	+51

Obtaining "meter-square" samples from an intertidal oyster bar (top), and (below) a large oyster bar exposed at low tide. Intertidal oysters are found in the warm waters of southeastern states but are restricted to deeper water in northern regions. (William Lang)

Conclusions

Estuaries usually contain high concentrations of nutrients. For the most part, this is a result of high concentrations of nutrients in the inflowing fresh water, but it may also be due to erosion of older marine sediments. The intimate contact of the sediments with the shallow estuarine waters is another extremely important feature. When organic matter decays at the top of the sediments, nitrogen and phosphorus are made available to the organisms in these shallow waters. Estuaries also have ways to prevent nutrients from being washed out to sea. One is the upstream movement of bottom water rich in nutrients; another is the sedimentation and coagulation of particulate matter. Both the circulation of water through the upper layers of the sediment and the resuspension of sediments into the water column serve to move regenerated nutrients from the sediments to the water. Also, both eelgrass and *Spartina* pump phosphorus from the sediments into the water column.

The high concentrations of nutrients entering estuaries and the mechanisms and processes that retain these nutrients within estuaries provide a rich nutrient environment for the growth of plants. These are mostly rooted plants and algae attached to the sediments or to large plant stems, because phytoplankton are usually washed out of estuaries before large blooms can develop.

Man's activities have fertilized the rivers and streams feeding many estuaries. Yet, this increase in nutrients has not changed the organisms present in most estuaries. In part this is because estuaries are naturally rich in nutrients. Also, blooms of phytoplankton algae never get the chance to develop in the same way that they would in fertilized lakes or reservoirs. Only when the natural circulation of estuaries is extremely slow or is interfered with will detrimental algal blooms develop. For example, the severe algal blooms in Moriches Bay and Great South Bay, Long Island (Ryther and Dunston, 1971), were caused by a combination of nutrient input from duck farms and a slow circulation of the estuary (reaction time of one month). Thus, estuaries have a number of mechanisms to conserve and utilize available nutrients. Estuaries can also deal with quantities of nutrients that would destroy the ecological balance of a lake or reservoir.

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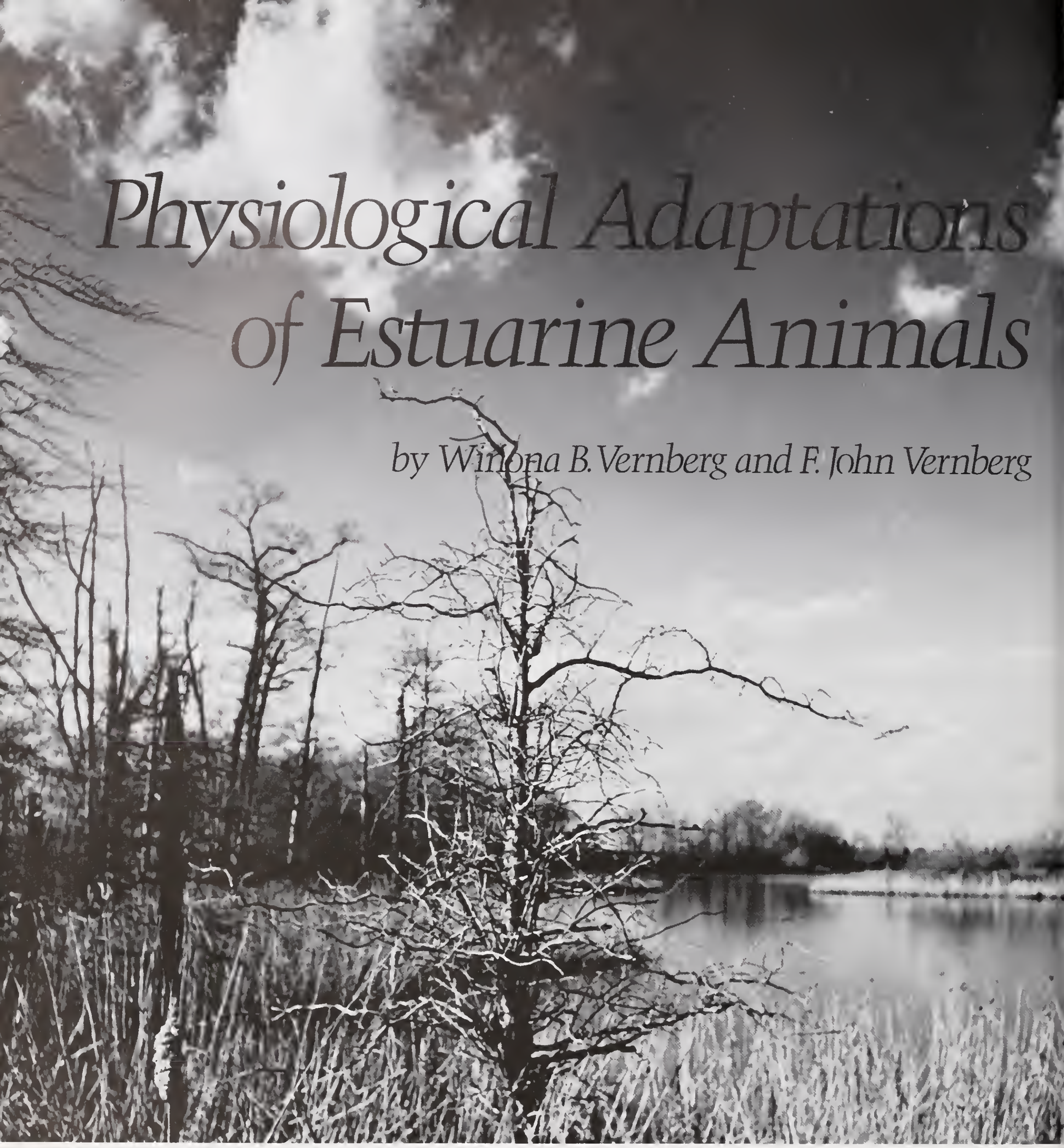

Physiological Adaptations of Estuarine Animals

by Winona B. Vernberg and F. John Vernberg

The estuarine environment is one in which water from a fresh water system mixes with seawater in a semienclosed region. As a result, one of its chief characteristics is a marked fluctuation in salinity. The amount of salinity change varies with the amount of fresh water runoff, and this may change on a temporal and seasonal basis. The amount of tidal fluctuation also affects the range in salinity flux. There are other fluctuating environmental factors that estuarine organisms also must face. Vast amounts of silt borne by fresh water runoff and deposited in the estuary form extensive tidal flats. The water bordering these tidal flats tends to be shallow, and temperature variations may be extremely pronounced during one tidal cycle or may be seasonally controlled by temperature changes in the open sea. Amounts of dissolved oxygen also may change markedly throughout a 24-hour cycle as a function of temperature and phytoplankton production. There are large amounts of organic material carried in with the fresh water, and estuarine waters generally are turbid, foreclosing the option of using vision in locating food, finding a suitable habitat, or seeking a mate. To the natural stresses common to estuarine existence we must also add those man-induced stresses—pollutants, thermal

Jock Sturges/Courtesy New England River Basins Commission)

additions, dredging, and filling—that have now become a part of the "normal" stresses of many present day estuarine systems.

Within this dynamic region lives a mixture of animals who have evolved the diverse physiological mechanisms needed to cope with fluctuating environmental conditions. To further complicate life in an estuary, a high degree of variability in environmental factors exists between different parts of an estuary. Thus animals inhabitating a region near the ocean endure a different environmental complex than those near the source of fresh water, while those in the water column experience different stresses than animals in the intertidal mud flats. Not only does environmental heterogeneity exist, but the various stages in the life cycle of a species may occupy different partitions of the estuary. This extreme variability of habitats and species is a delightful challenge to biologists concerned with understanding physiological adaptation.

One of the most fundamental and intriguing questions that can be posed is how it is possible for one group of animals to thrive under conditions that would be intolerable for another group. The physiological adaptations of a tropical zone species, for example, enable them to survive constant high temperatures that would quickly prove fatal to a species found in Arctic waters. Similarly, species living in estuaries are also well adapted to an environment that would be very stressful to fresh water or open ocean organisms.

When encountering a stressful situation, an animal has two alternatives: it can migrate to a more favorable environment, or it can remain and survive, depending on its adaptive capacity. If conditions are too stressful, the animal dies. However, not all stresses are of a nonliving origin, for organisms must compete intraspecifically and interspecifically for resources, such as space and food. The dynamic interaction of the animal and its environment is represented in Figure 1.

For each species there is a certain sector of the total range of expression of an abiotic environmental factor that is compatible with life. At either end of this gradient, there is a point beyond which an organism cannot survive. The broad middle sector that is compatible with life is called the zone of compatibility; the region at either end of this zone is the lethal zone (Figure 2). The dividing line between these two zones is not simply determined since numerous intra- and extra-

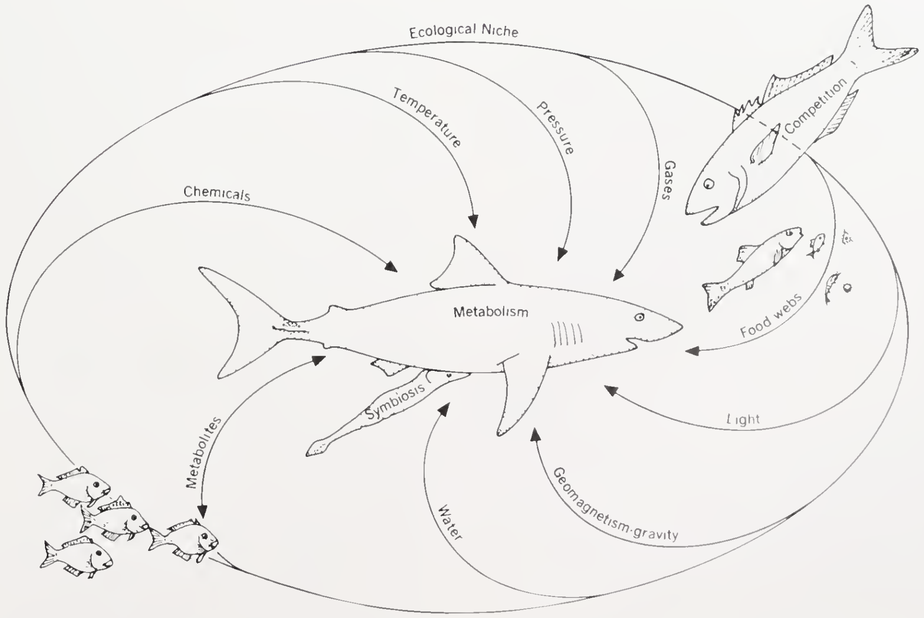

Figure 1. Interaction of an organism and its environment. (After Vernberg and Vernberg, 1972)

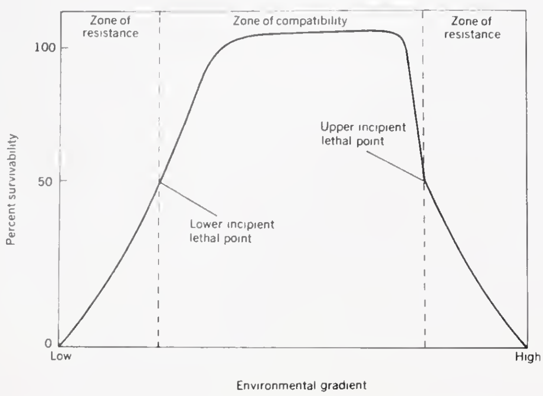

Figure 2. The zones of resistance (lethal zone) and compatibility. (After Vernberg and Vernberg, 1972)

organismic factors are involved, such as nutritional state and the possible interaction of numerous physical parameters. Differences in organismic response may reflect an altered physiological state (acclimation) due to exposure to a given set of environmental conditions. When the environment changes again, the animal adjusts by altering its physiological response. However, the range of these environmentally induced changes is determined by the organism's genetic composition and is not limitless. Different species have different genetic constitutions. Thus, estuarine species exhibit a wide range of physiological responses. For ease of presentation, the physiological diversity exhibited by estuarine animals will be discussed in the following two major sections: lethal zone and zone of compatibility.

Lethal Zone

Recently the alarm over pollution has heightened interest on the lethal effect of toxic substances on the estuarine biota (see page 18). But normal environmental factors also play a regulatory role on the distribution and abundance of organisms by disruption of their functional processes.

As salinity decreases, the number of marine animals decreases; a salinity range of 5-8^{o}/oo (parts per thousand) is apparently the critical salinity boundary between fresh water and marine faunas. A number of physiological processes appear to be involved; growth is impaired or stunted, reproduction is inhibited, and nerve conduction patterns are altered. In addition, the body fluid concentration of many brackish water animals can be reduced to a salinity of about 5^{o}/oo before serious damage results. Below this salinity, distortion of cellular electrochemical properties occurs and the tissue albumin fraction undergoes marked changes.

Typically, animals from the higher intertidal zone can withstand greater temperature extremes than those species living subtidally. For example, the oyster living in the intertidal zone survives higher temperatures than does the subtidal bay scallop. Of additional interest is that the response of the oyster can shift, depending on the previous thermal level of exposure, whereas the scallop's response is less labile. Thus, the thermal limits of the oyster can change with the season, an adaptive response for an organism that, by its sessile nature, cannot migrate when "environmental times" are difficult. Temperature changes have been shown to alter the biochemical pathways of certain animals, a change that apparently has energetic value. Not only do differences exist between species, but the responses of different stages in the life history of one species vary. For example, the adult fiddler crabs commonly found in marshes or intertidal beaches tolerate both higher and lower temperatures than do the larval stages that live in the water column.

Numerous examples demonstrate that other environmental factors, including oxygen, tidal action, sediment type, and species competition, may increase mortality levels. Although many studies have dealt with one of these factors at a time, the natural environmental complex obviously consists of all of these factors, and various combinations of factors may fluctuate at the same time. Although not as thoroughly studied, the results of multiple factor interaction investigation indicate typically that multiple stresses decrease the viability of organisms over that determined when only one factor is being stressful. Unfortunately, the physiological bases for this environmentally induced disruption of the functional integrity of organisms are poorly known.

Zone of Compatibility

Regulation of Water and Ions

The body fluids of many animals living in the open ocean have the same osmotic content as the surrounding seawater, and since this environment remains relatively constant, these animals do not have to face the problem of water balance. Estuarine animals, on the other hand, must have some physiological means to adjust to alternating high and low salinities. Otherwise, their tissues and cells would absorb a great amount of water when they encounter low-salinity water. One of two strategies, then, may be adopted by estuarine animals: they either have the capability to maintain an optimum osmoconcentration in their body fluids regardless of the external environment, or their tissues and cells have the ability to tolerate dilution.

Generally, animals are classified as being either osmoconformers or osmoregulators. An osmoconforming animal is one that does not regulate the osmotic concentration of its extracellular body fluid when that of the external environment changes. Instead, the concentration of this fluid conforms to that of the external environment. In contrast, the osmoconcentration of the extracellular fluid of an osmoregulating animal remains relatively constant when the external environmental fluid fluctuates in osmotic properties.

Animals in estuarine waters typically have the ability to hyperosmoregulate in low-salinity waters. Those which are semiterrestrial or live in areas subjected to rains, such as salt marshes and mangrove swamps, are capable of both hyper- and hypo-osmoregulating. That is, when salinities are low, they are able to maintain their extracellular body fluid at a higher osmotic concentration than the surrounding waters; when salinities are exceptionally high, they are able to maintain their body fluid at a lower osmotic concentration.

One osmoregulating mechanism that is commonly found is the walling off of the organism from the external environment, thereby preventing excess water and ion exchange. As a general rule, estuarine organisms tend to have body surfaces that show a marked decrease in permeability over those of oceanic ones. To gain impermeability, estuarine animals may show increased calcium deposits in the exoskeleton or have an increased number of mucous glands: they may also have morphological adaptations, such as opercula, to protect and isolate respiratory surfaces from adverse environmental conditions.

Animals living in fluctuating salinities often are confronted with an external milieu that is hypotonic to their body fluid. Under these conditions, the body fluids of the animal would tend to lose ions and/or gain water. The kidney or renal organ is of great value in both volume regulation and salt retention. There are some exceptions, but generally animals living in regions where they are exposed to low salinity tend to have more renal units, a greater total surface for glomerular filtration,

Shallow-water oysters being collected by long-handled tongs in a salt marsh creek. (William Lang)

and longer and more highly differentiated renal tubules that function for salt adsorption. The gills also play an important role in salt excretion and/or uptake.

Osmoregulating organisms may differ in the method of maintaining their osmotic concentration. Some polychaetes when exposed to low salinity are capable of active uptake of Na^+ and Cl^-, and the gills of the Chinese wool-handed crab *(Eriocheir sinensis)* can remove Na^+ from an external medium with a Na^+ concentration of 8 millimole, even when the internal Na^+ concentration is 300 millimole. Sharks have a relatively high blood osmoconcentration by maintaining a relatively high blood concentration of urea. Other species rely on changes in the amount of free amino acids in cells to maintain osmoconcentration. Organic substances, such as glucose, may also be used by animals to increase or maintain osmotic concentrations rather than relying solely on inorganic electrolytes.

Although osmotic regulation is important, the selective regulation of specific ions is essential. Protoplasmic integrity cannot be maintained in the absence or excess of certain ions. For example, Ca^{++} added to low-salinity water that is ordinarily lethal will enable animals to survive.

Feeding

In contrast to many pelagic systems, the primary producers in estuaries–and particularly in shallow, warm-water ones–include not only phytoplankton but also the marsh grasses, sea grasses, reeds, and other marsh vegetation. When this plant material dies, it is decomposed and becomes a part of the sediment as detritus. As a result, food chains in estuaries are based on this rich source of organic detritus derived from these various plants.

Feeding habits of the benthic estuarine organisms can be correlated with the hydrodynamic characteristics of their environment. In areas of slow currents where the mean diameter of sediments is less than 0.09 millimeter, most animals are detritus feeders. In areas where mean grain size exceeds 0.09 millimeter, filter feeding dominates, while predation is common where mean sediment size is greater than 0.15 millimeter.

Among the larger estuarine consumers, most are omniverous. Generally, they are able to utilize alternate foods from time-to-time and from place-to-place, depending on the stage in their life cycle and food availability. Thus, these animals can rely on detritus, a wide variety of bottom animals, and fishes. One of the most successful estuarine fish, the striped mullet (*Mugil cephalis*), illustrates well some of the aspects of estuarine nutrition. This species feeds on mosquito larvae, copepods, and other zooplankton until it attains a length of about 30 millimeters. Then it either feeds on detritus by sucking up the surface layers of mud, or browses on micro-algae attached to submerged surfaces. Sediment-feeding fish may take up small mouthfuls at random or may skim along the bottom, lips barely touching the sediment, and suck up the top layer. Both types of feeders strain a small quantity of the sediment by the pharyngeal filter and expel undesired material. Browsing animals nibble the attached algae, digest suitable food, and expel the remainder.

Respiratory Adaptations

To function successfully in a fluctuating estuarine environment, animals depend on functional metabolic machinery. Thus, it is not surprising to see striking and diverse types of adaptations. Reduced salinity may increase metabolic rate (rate of oxygen consumption) in some animals, while in others it remains unchanged or is decreased. The basic mechanisms that dictate these responses are unclear. Variability in response to oxygen content by various species can generally be correlated with the animal's mode of life. For example, the bottom-dwelling toadfish (*Opsanus tau*) can continue respiring and extracting oxygen from the surrounding water until almost all oxygen is removed, while, in contrast, an active surface-dwelling fish, the mackerel (*Scomber scombrus*), fails to withdraw oxygen when the oxygen content drops below 70 millimeters of mercury. In many animals, when the oxygen content decreases, the rate of oxygen consumption drops, but in other species the rate is unaltered. If the rate is unaltered, the animal must be able to remove more oxygen from the water even when the external oxygen tension is decreased. Various physiological ploys may be used to accomplish this, such as increasing the amount of water passing over the respiratory surface per unit time, improving the efficiency of removing a higher amount of oxygen from the water, or changing the amount and/or type of respiratory pigment. Prolonged exposure to a low but nonlethal oxygen tension may cause profound changes in the animal's metabolic performance, that is, a shift in biochemical pathways and/or the elaboration of new isozymes.

When the tide is out, the intertidal oyster closes its shell and shifts from an aerobic to an anaerobic metabolic system. In contrast, the fiddler crab (genus *Uca*) emerges from its burrow when the water recedes and shifts from anaerobic to aerobic metabolism. Thus, two intertidal species respond to tidal changes in a different manner. In general, those species living in oxygen-poor water differ from animals in oxygen-rich water in respect to their respiratory pigments. These are chemical entities that have a reversible affinity for oxygen and are found in blood, body fluids, and/or selective tissues. The respiratory pigments of animals from low-

*A female fiddler crab (*Uca minax*). Males are readily distinguished by having one large claw. (William Lang)* oxygen environments are more oxygen sensitive and will become saturated at lower oxygen concentrations than pigments of animals from high-oxygen areas, an obvious adaptive advantage enabling an organism to acquire oxygen from the water and transport it to the cells. The amount of respiratory pigment per unit volume tends to be higher in animals with a high rate of locomotor activity.

Perception of Environment

Animals living in the intertidal areas bordering an estuary will use vision in many life-supporting activities. In fiddler crabs, visual cues are very important during periods of low tide in moving about over the beach to different micro-environments to feed, reproduce, wet their gills, escape from predators, or release larvae. Many of these activities have directional components that are adaptive, and there is evidence that these crabs can use sun position and planes of polarized light as well as landmarks in carrying out their daily activities. However, animals living in the sediment-ladened water column of an estuary cannot depend on visual cues as readily as can either intertidal zone or open ocean forms.

Some estuarine animals are able to utilize tidal salinity changes to their advantage in seeking a suitable environment using rheotactic and chemoreceptive modalities. The European eel, (*Anguilla vulgaris*) illustrates well how such orientation is accomplished. After hatching in the tropical waters of the Sargasso Sea, the young larvae slowly migrate to inland waters along the coast of Europe and Africa. In the autumn of their third year, they metamorphose from willow leaf-shaped larvae into transparent elvers and become distributed along the European and North African coasts. The elvers are able to move into the estuaries in these areas with the tides by staying in the surface waters during incoming flood tides and then descending to bottom waters during ebb tides. By doing this they are able to avoid being washed out to sea. Day and night this pattern continues until they are in the estuary, and once there with the ebb tide flowing over them, they can distinguish between the overhead water masses. When a water mass containing inland water passes over them, they orient themselves by heading into the current and then make their way to inland waters to complete their development. The animals apparently are able to distinguish the specific odor of inland water by chemoreception, for inland water proved to be a very strong attractant, but the eels showed no response when exposed to tap water. There is evidence that other animals that breed in the sea but spend a part of their life cycle in the estuary utilize similar mechanisms for making their way to and from the open ocean.

Because visual display would be of limited value in estuarine waters, some fish rely primarily on audition for communication. The male toadfish (*Opsanus tau*), for example, has a well-defined spawning ritual. He first seeks a suitable nesting site, such as a tin can or a large empty shell, and stands guard. When he is ready to spawn, he emits a characteristic boat whistle call, which in turn acts as a stimulus to attract females that are ready to lay eggs. After the female lays a clutch of eggs, she leaves the nest, but the male remains until the young are free-swimming. If other fish approach the nest while the male toadfish is standing guard, he will emit a series of aggressive grunt sounds presumably to cause the intruders to leave the nest area.

Population Continuity

The animals living in the intertidal zone tend to lead a semiterrestrial existence as adults, but the larvae of most species live in the water columns within the estuary. Thus, the reproductive cycle must be geared to insure release of gametes into a favorable watery environment. Most mobile species migrate into a favorable environment to release their larvae, while the more sessile species must time the release of their reproductive products to coincide with periods when the adults are submerged. Since subtidal animals are always covered with water, when and where their larvae are released depends in large part on larval tolerance to estuarine conditions. For both intertidal and subtidal organisms to survive as a species, then, the larvae must be released when temperatures are not too extreme, salinities are optimal, and food is available.

How are the reproductive cycles of these organisms timed to insure that the larvae are released into a favorable environment? One very important factor is temperature. In some animals, spawning is initiated by a thermal change alone, while in others rising temperature and lengthening photoperiod interact to influence the reproductive cycle.

Reduced salinity reduces the reproductive potential in many estuarine species. Mobile species will move into higher-salinity waters to breed and spawn, while sessile animals tend to breed during seasons of the year when salinities are highest. There are some species, however, in which low salinity acts as a breeding stimulus, as illustrated by a number of species of fish in Indian estuaries. The peak of breeding activity in these fish occurs during the monsoon season, when salinities are at their lowest levels.

As is true of many marine animals, the reproduction of some estuarine animals is timed to coincide precisely with certain phases of the moon. Epidemic swarming has been linked to lunar periodicity in a number of species. The crab *Cardisoma guanhumi* offers a good example of this phenomenon. This crab lives intertidally and along drainage ditches on the south Florida coast, and it must return to the sea to spawn. The spawning season extends from late June to early December, and spawning occurs in sharp peaks near the time of full moon and in lesser peaks at new moon periods. Egg-bearing (*ovigerous*) females appear simultaneously, moving toward the sea, reaching the highest concentration between one night before the full moon and right after; then the spawning periods stops abruptly.

These, then, are some of the ways that estuarine animals are able to cope with their unique environments.

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Suggested Readings

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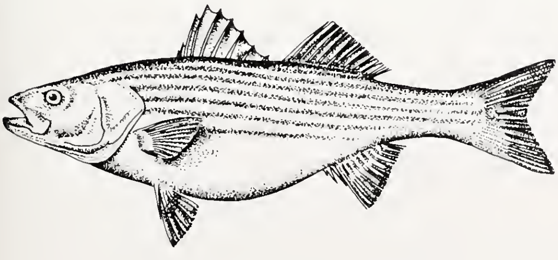
Fishes and Estuaries

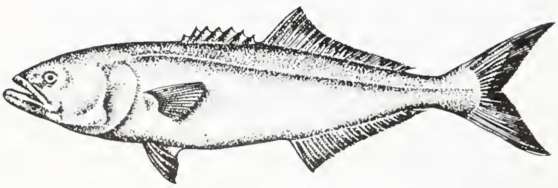
by R. L. Haedrich and C. A. S. Hall

Few areas of the earth support such large stocks of fish as do estuaries. Perhaps only African savannas and oceanic upwelling regions support similar concentrations of vertebrate biomass (Table 1). Studies of the total biotic energy fixed by plants and used in these places indicate that, in general, estuaries have the greatest availability of food of any region in the world (Odum, 1971; Teal and Teal, 1969; Woodwell, Rich, and Hall, 1973). These conditions have made estuaries rich feeding grounds for fishes, and it is also here that man takes his greatest harvest of sea foods. Five of our six most important commercial fish species are dependent in some way on estuaries (Smith, 1966).

Scientists have been impressed by the degree to which these regions are "stressful." The many abrupt changes in temperature, salinity, and chemical and oxygen concentrations over seasonal, daily, and tidal cycles imply a high degree of physiological stress on estuarine organisms. Many studies have shown that the physiological cost of adaptation to such conditions is high. Why should areas of such a high degree of stress have so many fish? And why should some estuarine fish groups, such as salmon, evolve life histories involving long-distance migrations that appear to increase their exposure to stress?



Striped Bass (*Roccus saxatilis*)



Bluefish (*Pomatomus saltatrix*)

Sampling Problems

The first problem in attempting to answer these questions is getting a good sample. Unlike clams and diatoms, fish are too clever and too mobile to be passively captured in most sampling gear. No one piece of gear is fully adequate. The seines suitable for smelt do not retain sand eels. Trawls are fine for winter flounder and juveniles of some fish, but not for eels, which must be trapped. Mummichogs lend themselves to trapping, but then the eels in the trap eat them. Weakfish and bluefish are perhaps best angled for. For most sampling procedures, the sample is, at best, only semiquantitative.

However, there are several ways that one can get, albeit with considerable effort, reasonably good quantitative estimates. One way is to catch a large number of fish, tag them, and then derive population estimates according to the number of tagged fish that are recaptured. Tagging is doubly useful. Not only does it allow population estimates to be made, it also provides a way of tracing the movements of the fishes. But tagging is not always an easy matter. Large fishes, such as striped bass, white perch, and salmon, are not difficult to tag, and because these are important game fish, tags can be recovered without too much effort by enlisting the aid of sportsmen. Small, delicate fishes, such as silversides and young alewives, may be almost impossible to tag. Even if they could be, a considerable recapture program would be necessary.

Where physical tagging is impossible, indirect statistical methods can be used, such as following year-classes or using egg-and-larva surveys. Such approaches can be used only for those few species that show little migratory tendency and that are sampled readily in all growth stages throughout the year. We know relatively little about the lives of estuarine fishes, but we do know enough to say that hardly any fit this requirement.

Sonar offers some hope for extensive and accurate surveys of estuarine fish. Some day it may be possible to have computer memories of sonar "fingerprints" for different species and online print-outs of species-by-species biomass. However, many technical problems remain, and it will be a long time before any such system is routine.

One recently "rediscovered" method holds promise for giving quantitative estimates in some estuarine environments. This is the drop net, conceptually similar to the quadrate used by field botanists (Figure 1). A horizontal, chain-bordered net is dropped randomly or according to some sampling plan, and the fish that are caught are identified, counted, and weighed. The method works well in estuaries that are less than 2 meters deep with an uncluttered bottom of sand or mud. There are problems, however, associated with the use of the drop net. For example, fish may be either attracted or repelled by the net's frame. We have found that in turbid environments, where there seems to be little or no gear selectivity, the drop net gives an accurate estimate of biomass. We caught virtually no fish in a standard otter trawl used in areas where we measured 50 or more grams per square meter of fish with the drop net.

The Fish in an Estuary

Assuming the sampling problems are solved, what types of fish will be found in the nets? Phylogenetically, many important marine groups are represented in the estuarine assemblage of fishes. The New England assemblage is dominated (relative to their contribution to the total fauna) by salmoniforms (trouts and smelt), atheriniforms (silversides and mummichogs), and gasterosteiforms (sticklebacks). These are the groups whose basic adaptations are to an estuarine existence. Otherwise dominant marine groups—the gadiforms (cods), clupeiforms (herrings), anguilliforms (eels), and perciforms (basses, perch, and other spiny-rayed fishes)—are represented in the estuary by only a relatively few species. In these groups, it is some specific adaptation, not an adaptation of the group as a whole, that allows the fish to thrive in the estuary.

In many cases it is difficult to characterize a fish as "estuarine" or "marine." Tagging studies show that certain fishes may range quite far from the estuary where they spend at least a part of their lives. The movements of salmon are among the most extensive. The oceanwide wanderings of the five species of Pacific salmon have been known for some time, but only recently has it become apparent that the Atlantic salmon moves quite far as well. Results of tagging indicate that fish from both European and North American rivers congregate in the rich waters off Greenland, where they feed and fatten before

Table 1. Biomass in certain ecosystems.

Group	Area	Grams per square meter
Birds	New Hampshire forest	0.04
Moose	Isle Royale, Michigan	0.7
Humans	United States	0.9
Fishes	Unpolluted rivers	1-5
Fishes	Georges Bank	1.6-7.4
Fishes	Atlantic salmon river, Matamek, Quebec	2.1-17.8
Fishes	Narragansett Bay	3.2
Large mammals	Central and East African grasslands	3.5-23.6
Fishes	Gulf of Mexico	5.6-31.6
Fishes	Flax Pond (Long Island) Estuary (annual average)	24.0
Fishes	California kelp bed	33.2-37.6
Fishes	Bermuda coral reef in summer	59.3
Fishes	Narragansett Bay salt marsh embayment	69.2
Anchovy	Peruvian upwelling in autumn	216.7

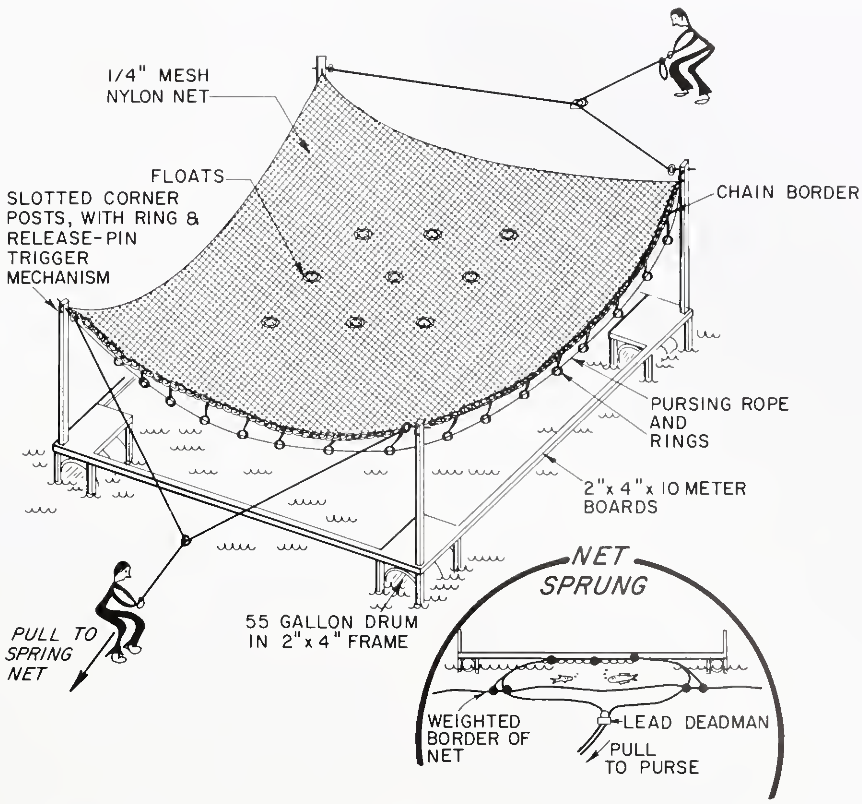


Figure 1. A drop net used in estuarine sampling.

returning to home rivers to spawn.

To encompass these apparent oceanic excursions and at the same time to keep in mind the essentially estuarine focus of such fishes, McHugh (1967) introduced the interesting notion of an extended estuarine zone. The definition of this zone depends not on man's terrestrial and topographic viewpoint, where the estuary extends hardly beyond the capes that guard a river's meeting with the sea, but rather on the fish's aquatic and hydrographic viewpoint. Salinity is the important characteristic. The flow of rivers in some places, most markedly the North Pacific, and an excess of precipitation over evaporation in others result in vast shallow lenses of low-salinity water overlying water of more oceanic characteristics. McHugh's chart of the offshore estuarine zones, as bounded by the 33.5°/oo (parts per thousand) isohaline shows that these have considerable extent (Figure 2). The largest offshore estuary includes almost the entire North Pacific north of about 40°N, where an estuarine analogy had earlier been argued by Tully and Barber (1960). The Northwest Atlantic Estuary extends from Cape Hatteras to Labrador.

The boundaries and even the appropriateness of the extended estuaries can be argued, but the concept of a seaward extension of the estuary must remain an important one for fishes. Many species for which the conventional estuary is an important habitat at some stage in their lives are found well offshore at other times. The salmons, again, are the most extreme examples. The list of New England fishes would have to include, in addition to Atlantic salmon, the sturgeon, sea lamprey, American eel, shads and sea herring, weakfish, butterfish, bluefish, and winter flounder.

Figure 2. Offshore estuarine zones of the world bounded by the 33.5°/oo (parts per thousand) isohaline. These shallow lenses (shaded areas) overlie water of higher salinity. (After McHugh, 1967)

An Atlantic salmon on its upriver spawning migration in the Miramichi River, New Brunswick, Canada. (John Gibson)

Another group of fishes is more closely associated with the estuary proper, and its members are rarely found more than a few miles from shore. In New England, such fishes are the smelt, salters (sea-run trout), sticklebacks, pipefish, silversides, mummichogs, tomcod, kingfish, striped bass, and white perch. The list is not large. Even with the species of the extended estuary added, the total is only about 10 percent of the total marine fish fauna of the New England coasts and shelf (Bigelow and Schroeder, 1953). Nonetheless, members of this group have considerable economic importance and are particularly sought by both commercial and sport fishermen.

Physiological Aspects of Estuarine Adaptation

The great range in temperature and in salinity that can be encountered in the estuary could place considerable physiological stress on a fish living there. Despite the ability of most fish to move about and adjust their local environment, some degree of temperature tolerance and osmoregulatory ability would be required to cope successfully. Such physiological adaptations are among the most important, if not the major ones, that an estuarine fish must possess.

The predominantly estuarine species belong to groups that are tolerant of wide ranges in temperature and salinity. The salmon and their relatives, many of which move from salt to fresh water to spawn, have the ability to adjust rapidly to great changes in salinity, as do sticklebacks and killifishes (mummichogs). Salt balance in these species is achieved through a generally low permeability of the body surfaces and marked activity of the kidneys and salt glands in the gills.

Near-freezing conditions are met by the winter flounder through a seasonal change in the blood serum chemistry, which depresses the freezing point. In the Hudson River, striped bass move into relatively fresh water to overwinter. The cold, saltier water of shallow bays, with a depressed freezing point, has the potential to freeze the fishes' blood.

Winter flounder, striped bass, tomcod, and others have individually adapted to estuarine conditions, although the group to which each belongs tends on the whole to be less tolerant of extremes. We do not know how great is the energetic cost for an estuarine fish to maintain the complicated biochemical, physiological, and behavioral arsenal it requires to exist in the estuary, but it cannot be inconsiderable.

The Natural History of Estuarine Fishes

A broad spectrum of ecological roles is played by fishes in estuaries. Most of the information available on feeding has been summarized by de Sylva (1975), and his list of references is surprisingly short. However, even in the New England estuaries that contain few fish species, many patterns of feeding are found. Mummichogs feed on detritus and small invertebrates, which they hunt in marsh channels and in the *Spartina* grass. Schools of silversides move over the more sandy areas preying on small crustaceans in the water. Winter flounder feed omnivorously on the bottom, but concentrate on worms, isopods, and small clams. Smelt feed up in the water column on sand shrimp and on small fishes, not infrequently their own young. Eels, too, feed on small fishes but presumably nearer the bottom and generally at night. Young alewives and menhaden strain zooplankton as they swim. Carnivores, such as bluefish, are active during the day, feeding on herrings and silversides, while striped bass prey on smaller fishes, eels, and seaworms, especially in the evening and at night.

The estuary is a spawning site for only some of the fishes found there. In New England, the winter flounder lays large clusters of adhesive, nonbuoyant eggs during the coldest part of the year—winter into early spring. The tomcod lays large numbers of nonbuoyant eggs somewhat earlier, from late fall into winter. The production of sticky, nonbuoyant eggs must be a particular adaptation to keep the eggs within the estuary, for the closest relatives of both these fishes, which live offshore, lay pelagic eggs. Mummichogs spawn in spring, when large schools crowd into small tidal creeks. The males become very brightly colored and ardently court the females. The large eggs are laid in shallow water, where they stick to rocks and plants on the bottom. The silverside waits until a warmer part of the year, late spring and summer, to spawn over sandy bottoms and near the base of the *Spartina,* where the abundant eggs adhere with long sticky filaments. Sticklebacks do not rely on great numbers of eggs to insure survival. Instead, the male stickleback builds a small nest of plant material during spring and into summer. After an elaborate courtship, a few sticky eggs are spawned within the nest. The male guards them until hatching and even for some time thereafter. The pipefish goes the stickleback one better. In this species, the eggs, laid in the summer, are brooded by the male in a special pouch on the abdomen. In all these species, incubation is fairly rapid and ranges from about a week in silversides and the stickleback to about three weeks in tomcod.

A number of important estuarine fishes spawn not in the estuary, but in the fresh water upstream. Of New England fishes, these include the smelt, alewives and shad, sea-run trout and salmon, and the striped bass. Smelt are the earliest spawners, ascending rivers and brooks in late winter and early spring, the coldest time of the year. They generally run only a short distance into fresh water, sometimes just above the tideline, although in some large river systems they may run more than a hundred miles from the sea. The eggs are laid in large sticky mats on the bottom in running water. Immediately after hatching, in about two weeks, the young drop down to the estuary.

When the water has warmed a bit in the spring, and when the shadbush blooms, the alewives begin their spawning run. These fish require fairly still water to lay their eggs, and thus ascend only rivers or brooks that drain from ponds. The eggs are laid in masses that sink to the bottom and adhere there until hatching, about a week later. Like the young smelt, small alewives move down to the estuary fairly soon. Trouts and Atlantic salmon move into fresh water generally in the spring and early summer but do not spawn until fall. They may run for long distances, well up into the cold, well-oxygenated headwaters. These fish bury their eggs in gravel bars, where the eggs overwinter to hatch in the spring. The young spend two to three years in the river before drifting down to the sea.

A prime example of this fresh-water spawning pattern, called anadromy, is found in the striped bass, a popular sport and commercial fish. Stripers are rarely caught more than 10 kilometers from shore, and estuaries are essential for their reproduction and early life history. Stripers apparently require some 100 kilometers of free-flowing fresh and/or brackish water to successfully spawn, and as a result, they spawn only in the largest estuaries. The Hudson, Delaware, and the Chesapeake systems have traditionally been important spawning areas for the stripers, although dams and pollution have eliminated Delaware spawning. Fish spawned from these estuaries migrate northward during the summer to support extensive coastal fisheries in New York and New England. On the West Coast, where the striper was introduced in 1879, the Sacramento River is a spawning center.

Talbot (1966) reviewed the life history of the striped bass and documented the crucial role that the estuarine ecosystem plays. The following account of striped bass in the Hudson River is based on the work of Talbot and others, as well as on analyses developed at Oak Ridge National Laboratory as part of environmental impact studies for Hudson River power plants.

The fish spawn in late May or early June above the salt water (Figure 3). The semibuoyant eggs and larvae appear to spend some days or weeks very near the bottom of the river, drifting little as the bottom currents are not strong. By about two weeks of age the young bass are found throughout the water column and begin to drift downstream. As the fish become strong enough to swim feebly, they begin to migrate vertically, moving toward the bottom during the daytime and to the surface at night. Once within the influence of the estuarine salt wedge, the young fish are swept seaward during the night in the relatively fresh surface water, and upstream during the day when nearer the bottom. At about six weeks, the fish are able to maintain their position by swimming against the current, and at this time the majority of the fish are found in shallow regions in Haverstraw Bay and the Tappan Zee, the broad bays below Peekskill, New York, downstream to the New Jersey state line. A smaller number are found along the shoreline.

The daily migration pattern of the two-to-six-week-old fish appears to be a critical factor. Without this pattern, the young fish would be too weak to swim against the seaward-flowing surface waters and would be swept to sea if they remained in the main currents. If they remained entirely on the bottom, they would be moved upstream above their nursery grounds. The salt wedge is normally associated with the biotically richest regions of estuaries, and fish that exhibit a pattern of diurnal vertical migration would be concentrated in the region of highest available food supplies (Figure 4). As many other anadromous fish also show this pattern, it seems clear that selection has taken place for such a behavioral pattern in the young of many estuarine fish species. Pearcy (1962) has

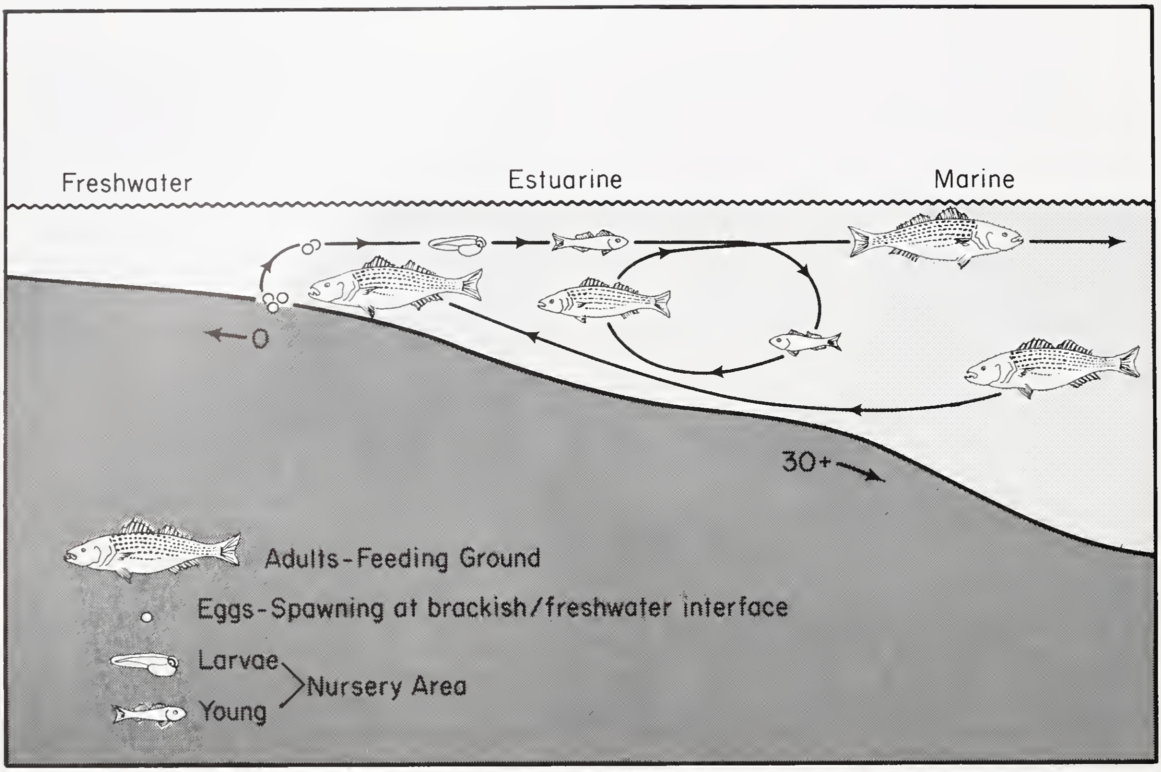


Figure 3. The striped bass, an important estuarine species, is a semianadromous fish, moving from saline water to, or almost to, fresh water to spawn. It usually spawns near the interface of fresh and low salinity water. In the estuary the eggs and larvae drift downstream, and the developing fish feed throughout the system until they reach maturity and repeat the cycle. (After Cronin, L. E., and A. J. Mansueti. 1971. The biology of the estuary. In A Symposium on the Biological Significance of Estuaries, *Sport Fishing Institute, Washington, D.C.)*

shown a similar migration pattern for larval flounders, and the salt wedge circulation pattern is probably also important for young Pacific salmon.

Less is known in detail about the estuarine fishes that spawn in the sea. Butterfish and bluefish spawn well offshore, but the distribution of their eggs has only recently been documented by the National Marine Fisheries Service. The young quickly make an appearance in the estuary where they feed and grow. The eel is the apparent long-distance champion. Its eggs are unknown, but the smallest larvae first appear in the southeastern Sargasso Sea, where they spend a year drifting in this great oceanic gyre. In the spring, young elvers move into the estuaries. Some remain there, but others continue to migrate far up rivers and brooks. The eel makes most of its growth either in estuaries or in fresh water. In the fall, some, but not all, of the adults migrate down and out to sea, presumably to their unknown, remote spawning rendezvous.

Regardless of the spawning pattern, the time at which many juvenile fishes reach the estuary is closely coincident with periods of maximum food production. The fish may be evolutionarily programmed, so to speak, to take advantage of pulses in food just at the stage in their life when they are growing the fastest. For example, our analysis of Pacific salmon indicates that the young enter coastal waters at just the right time to catch the large, and predictable, pulse in zooplankton. The zooplankton pulse, in turn, follows the spring phytoplankton bloom.

Most of the fishes that spend their juvenile periods in estuaries do not stay there as adults. This is particularly true for the shallow regions that

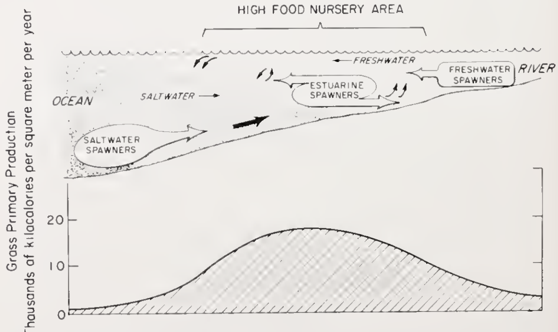


Figure 4. Spawning patterns and the salt wedge in an estuary. The graph indicates mean primary production across the region.

are most important as nursery areas. Perhaps the shallower regions are uncomfortable for large fish, but we have often wondered whether there is a more fundamental reason why large fish do not "cheat" by feeding more heavily in shallow nursery areas. Adult salmon are found far at sea and younger salmon nearer to shore. Juvenile snapper blues are familiar residents of shallow estuaries, but the adult bluefish tend to be found further offshore where potential food is more limited. Many possible explanations come to mind, of course, but there may be selection pressures to allow the younger fish free access to the most productive estuaries.

A few generalities emerge from these brief considerations of natural history. A variety of feeding patterns is present in the estuary, which means that the food resource in general is shared among the fish species. The estuary seems most important, not as a spawning area, but as a feeding and nursery area for the young of many species, regardless of where they spawn. For those species that do spawn in or near the estuary, the production of large numbers of adherent demersal eggs that develop and hatch in a very short time appears to be the rule. Direct competition is avoided by the use of different areas and times for spawning. The observation that dominance by a few species tends to be the rule in estuarine fish communities follows from the large spawning aggregations and the great numbers of young produced. In New England, two to four species make up 80 percent or more by numbers of the fishes found in an estuary.

A Hypothesis of Seasonal Use

It is clear that fishes make varied demands on estuaries. The pressure of these demands varies throughout the year, particularly for species with seasonal patterns of reproduction and growth. Seasonal comings and goings further enhance a picture of seasonal change. We have argued (Haedrich, 1975) that seasonal change in the local fish community should be quite marked in the healthiest temperate estuaries. Seasonality allows multiple use, and evolution and co-adaptation within the community permit the greatest possible number of species to share the resources. The estuarine environment from which the most species can benefit—the estuary with the highest annual species diversity—should be the one where a good seasonal turnover occurs. Where the environment is rendered less equitable—for example, by pollution—the number of species which can use that area will be reduced. Gradually the more sensitive species will drop out, leaving only the most hardy. Those that remain will be those basically adapted to the greatest extremes of an inhospitable climate. Such fishes, presumably, would be ones already attuned to estuarine life.

What little comparative data there are seem to bear out this working hypothesis. In Woods Hole Harbor, a relatively unpolluted area, 38 species were taken in trawl samples made during the course of a year (Figure 5). There was considerable turnover both in species present and in relative abundances from season to season. Percentage similarity (an index that takes the presence and abundance of species into account; it ranges from 0 percent where there is no overlap to 100 percent where overlap is total) from spring to summer was 16 percent; from summer to fall, 52 percent; from fall to winter, 34 percent; and from winter to spring, 69 percent. Four species accounted for 80 percent of all individuals. Lynn-Saugus Harbor, Massachusetts, a polluted area where 93 percent of the clam flats were closed because of gross contamination, had only 21 species trawled throughout the year. The lowest value of similarity between seasons was from fall to winter, where it was still quite high at 75 percent. From summer to fall it was 86 percent. A single species comprised more than 80 percent of all individuals. That

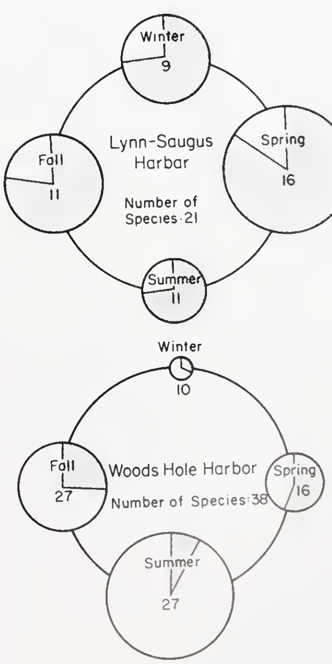


Figure 5. The annual cycle based on the number of species in Lynn-Saugus Harbor and Woods Hole Harbor, Massachusetts. The area of each circle is proportional to the catch rate, the number in each circle is the number of species, and the number on the connecting arrow is the percentage similarity between seasons. The shaded portion in each circle represents the winter flounder fraction.

Alewife (*Pomolobus pseudoharengus*)

species was the winter flounder, a fish adapted to estuarine life under severe conditions. The data are intriguing, but far more are needed.

Circulation Patterns and Biotic Productivity

We have discussed one direct relation of estuarine circulation patterns to fish life history. But there are other, indirect relations. Redfield (1967) was among the first to note the potential importance of density circulation patterns (for example, the two-layered flow associated with the salt wedge) to estuarine primary productivity. Riley (1967) described the mechanism by which coastal waters are enriched by the inward movement of deeper nutrient-rich oceanic water. Thus, during the warmer months, when the stratified surface of coastal waters is depleted of nutrients, the salt wedge provides a mechanism for enriching areas off river mouths. The inward-moving, nutrient-rich deep water is mixed upward in the vicinity of the salt wedge. Then the nutrients are available for the phytoplankton. The term perhaps most appropriate for the input of nutrients to coastal waters by inward-flowing, density-driven deep waters is inwelling. Some of our ongoing work is examining the relative importance of land-derived and inwelling-derived nutrients in the North River, Massachusetts, estuary.

Sutcliffe and his associates at Bedford Institute of Oceanography in Canada further developed the conceptual relationship between circulation patterns and estuarine productivity by looking at the relation of the nutrient inflow pattern to both primary production and fish production (Sutcliffe, 1972, 1973). This work emphasizes another important aspect of estuarine circulation patterns. The influx of deeper salt water is a function of the quantity of fresh-water discharge: the greater the fresh-water efflux, the greater the salt-water influx, since both the friction (and hence net upward entrainment of salt water) with larger runoff and the associated eddy turbulence are greater. Of course, with greater discharge, the entire zone of mixing may be moved offshore.

Sutcliffe found larger concentrations of phytoplankton-sized particles (and, by inference, greater primary production) in the Gulf of St. Lawrence following periods of intense discharge of the Saint Lawrence River. Of even more interest is that he found a highly significant correlation between the catch of commercial fish and lobster, adjusted for the time interval between birth and entrance to the fishery, and the discharge of the St. Lawrence River (Figure 6). The inferred mechanism behind this relation is that heavy fresh-water discharges pump more nutrient-rich salt waters into the estuarine fish nursery grounds, increasing phytoplankton production and improving survival of fish during their first few months, a highly critical time in their development. Although much more work must be done before we understand the generality of Sutcliffe's hypothesis, it is obviously a fertile area for research.

Two practical extensions emerge from Sutcliffe's work. First, it may be possible to make predictions of future fishery yields on the basis of river discharge. If river flows are heavy during a given spring, good fish catches can be expected after as many years as it takes for the fish to enter the fishery. The second important aspect applies to fisheries management. As we increasingly dam coastal rivers, we increasingly damp the spring runoff pulse. Fish species programmed to exploit such pulses of productivity may become less abundant. With proper management the seasonality and extent of estuarine productivity could be regulated by timed releases of water from rivers that are already dammed.

An Approach to Ways Fish Utilize Estuaries

While estuaries are rich in fish life, we have noted that there are substantial physiological costs to fish living in estuaries. We also have said that fish are strongly seasonal in their use of estuaries, particularly temperate ones. Sufficient benefits must result for the fishes to adapt to estuarine stress and to migrate

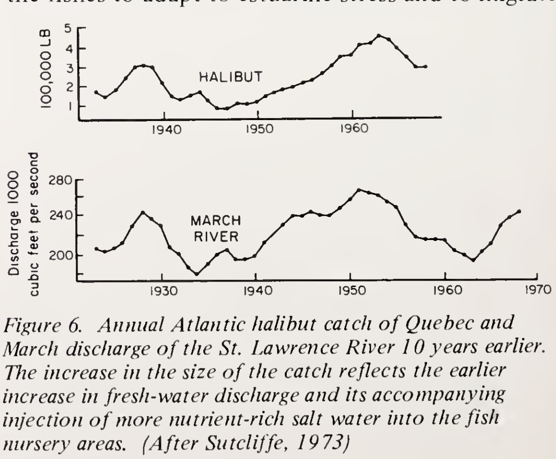
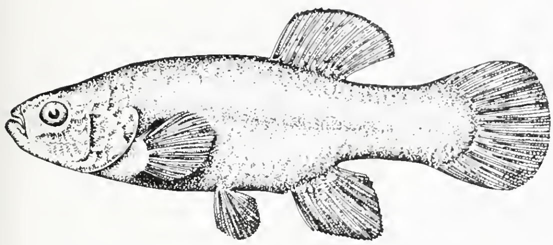


Figure 6. Annual Atlantic halibut catch of Quebec and March discharge of the St. Lawrence River 10 years earlier. The increase in the size of the catch reflects the earlier increase in fresh-water discharge and its accompanying injection of more nutrient-rich salt water into the fish nursery areas. (After Sutcliffe, 1973)



Common Mummichog (*Fundulus heteroclitus*)

in and out of estuaries. These benefits are related to the high primary productivity of estuarine waters, which are frequently more productive of plant material than neighboring rivers or seas. How, then, can we integrate this information: large fish stocks, patterns of primary production, seasonal use, and physiological stress? One way is by constructing an energy "cost/benefit" analysis. Expressing biomass and activities in terms of energy as the common denominator, we can analyze costs and benefits in equivalent units.

Temperate regions are marked by spatial and temporal variations in primary productivity, and these patterns are especially pronounced in estuaries. Such seasonal patterns can be capitalized on by migratory species, which make it their business to be where seasonal pulses in productivity occur when they occur. We can quantify the benefits to fish of tapping pulses in primary production: it is equal to the primary production of a region times the conversion coefficient of primary production to fish. Such data are already available to an approximate degree for some fish and regions, and the numbers are easily converted to calories (energy).

But what of the energy costs? The first is the cost of migrating from one region to another. Fortunately, extensive data can be found in the physiological literature on the energy cost of swimming under various conditions. The next question is the energy cost of physiological adaptation to different and frequently varying environments. This can be estimated from the additional oxygen that a migratory fish, such as a salmon, uses when exposed to different environmental conditions, and there are data on this.

To our knowledge such a cost/benefit analysis has not been done for an estuarine fish. Hall (1972) did make such an analysis for fresh-water migratory fish and demonstrated that the energy gained by exploiting spatial and temporal variations in primary productivity would be at least three times greater than the energy used in migration from one region to another. We are now in the process of extending this type of analysis to Pacific salmon. Fortunately, quantitative information is available concerning the dynamics and natural history of Pacific salmon stocks, the energy needed by salmon to swim, and the seasonal and spatial patterns of primary productivity in the different regions occupied by the salmon at various times in their lives. We are attempting to integrate this information in a cost/benefit analysis, and hope to extend the analysis to an evolutionary perspective to see whether there would be selection for a migratory gene appearing in a nonmigratory salmon population. We believe that such studies will help us understand why the salmons, as important estuarine fish, have evolved their characteristic and rather complex life cycles.

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Drawings by Nancy Barnes, after Bigelow and Schroeder.

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Constitutional Issues and Estuarine Management

by John S. Banta

The changing of wetlands and swamps to the damage of the general public by upsetting the natural environment and the natural relationship is not a reasonable use of that land which is protected from police power regulation.

Just v. Marinette County,
Wisconsin Supreme Court (1972)

Important local, state, and federal regulatory programs are imposing tough restrictions on the right to develop and use land in estuarine areas. In recent years, virtually all of the states on the Atlantic coast have adopted or seriously considered new laws to conserve wetland resources. The Federal Water Pollution Control Act Amendments of 1972 added a new section, 404, extending federal permit requirements for development activity upland beyond the traditional limits of navigability. Local governments have used zoning and subdivision powers to manage wetlands and flood hazard areas.

These programs apply to private property as well as to public lands. Owners are alarmed by regulatory restrictions that may make small lot subdivision and some types of development impossible. Some look to special provisions of state statutes and constitutions for compensation. Others press for a court examination of the legal and constitutional limits on government authority over the use of land. Many find both consistent compensation rules and clear limits on government authority difficult to identify, particularly in the estuarine context.

On the one hand, there is a powerful myth among landowners that the Fifth Amendment to the United States Constitution—. . . *nor shall private property be taken for public use without just compensation*—protects them from regulation that restricts use of property (*The Taking Issue*, Government Printing Office, 1973). The myth finds little support today among the state and federal courts.

Likewise, there is a spreading fear that government at all levels can take private land, through zoning and environmental regulations, for public use without paying compensation. Though unfounded, the fear is fostered by the exceedingly complex ownership and regulatory situation posed by water areas associated with estuaries. This fear is grounded in the same confusion that supports the myth and poses similar practical and political problems in developing management programs for sensitive ecosystems, such as estuaries.

The Taking Issue

A landowner whose land is slated for expropriation as a recreation area or public refuge is protected by the Fifth Amendment. Acquisition procedures are watched closely by the courts. Acquisition must be for legitimate public purposes, which may be questioned in court, and the government must provide "just compensation," usually defined as the fair market value of the property, excluding any influence from the proposed public improvements. The taking issue only arises when a regulation, such as a zoning ordinance, restricts the use of private land.

However, though private land may not be opened for use by regulation, some of the objectives served by the publicly acquired wildlife refuge—protection of endangered species, water quality, and wetlands function—may also be legitimate regulatory objectives. A regulation adopted to serve these purposes and based on police authority may substantially restrict the use of land without any provision for compensation. Depending on the general position of a state's courts, the probability of success in a court challenge to eliminate restrictions on use may range from slight to substantial.

For many years after the founding of the country, there was no opportunity for court review of regulations as a "taking." It was only after the turn of this century that constructive or regulatory taking was recognized. Some types of regulatory situations moved to a grey area where they could be considered in court and declared an invalid taking. About the only generalization that is easily supported is that the transition between valid and invalid regulation today is somewhere short of complete prohibition of all use of private property.

The uncertainty has been compounded by the absence of clear rules from the United States Supreme Court. The classic constitutional test for invalidity has been described as a balancing of the public purpose of a regulation against the private harm borne by a landowner; if the balance tips in favor of the landowner, the regulation is unconstitutional and invalid. In most cases, courts arrive at the Supreme Court rule in the landmark Pennsylvania Coal case: *The general rule at least is, that while property may be regulated to a certain extent, if regulation goes too far it will be recognized as a taking.* This vague statement, written by Justice Holmes in 1922, is applied today in state courts through a composite of special considerations applied in differing circumstances, often giving little more specific guidance than the Court offered in 1922.

The most important factors that affect the rule applied in the water areas of estuaries are: (1) the public purpose served by the regulation that is open to challenge; (2) competing public interests in the affected property (easements, public trust, navigation rights); and (3) loss of value. None give a firm guide to the constitutional limits of government regulation, but they form the first point of reference.

Public Purpose

Regulations for the protection of wetlands and estuarine areas find their constitutional roots in police power, or the power to protect public health, safety, and the general welfare. Early regulations were adopted to prohibit nuisances, such as noise, odor, or dirt. Nineteenth-century coastal restrictions covered sand and gravel removal that threatened protective natural features. A court in Massachusetts, which was asked to review the efforts of Plymouth in the 1850s to protect its harbors, beaches, and sand bars, saw a prohibition on gravel removal as a natural and legitimate objective.

Today regulations are related to local, state, and national programs that affect estuarine areas—coastal zone planning, flood insurance and coastal high hazard protection, dredge and fill regulation, and water quality planning and management. Their provisions include complex resource protection objectives.

Resource management purposes were viewed with skepticism by the courts in the 1960s as regulations for flood plains, wetlands, and water quality began to emerge. Some courts looked to intended uses to describe purpose. For example, a zone for meadows conservation, which only permitted power lines, radio transmission towers, and other public and quasi-public uses along with farming, was held invalid in New Jersey. The court viewed the zoning provision as an inappropriate effort to acquire public rights in private property.

New Jersey's courts have since indicated approval of flood plain zoning and wetlands management, though their earlier strong statement about the acquisition of public rights in private property through regulation remains influential and has not been overruled.

Some discussions of public purpose distinguish situations where similar restrictions—for example, a no-build standard in a floodway, or for open space—are treated differently by looking at the public purpose served. Some public purposes seem to be considered "heavyweights" in a court's balancing test and justify especially tough regulation. Actions to block or eliminate nuisances—rock quarries or dirty industry—are traditional heavyweights. Regulations for these purposes have been the type most frequently considered by the United States Supreme Court. The Court has firmly rejected taking arguments in most cases. As a result, most Supreme Court decisions have recognized tough regulations as legitimate without compensation, but the Court has not considered the hard cases where sound public purpose shades into arbitrary public judgments. At this extreme are aesthetic judgments, such as landscape and architectural design. A long battle over unsightly advertising signs has fueled this legal discussion. Complex amortization and compensation provisions are often added to this type of regulation to adjust the balance of public purpose and private harm.

Coastal environmental legislation does not clearly fit into either category. As coastal ecosystem diagnosis becomes more precise, nuisance-like effects are more easily identified. But in the interim, courts have been influenced by legislative findings that capsulize the considerations supporting particular regulatory programs.

The New York Adirondack Park Agency is

The Elizabeth/Newark, New Jersey, Port Authority Marine Terminal with adjacent wetlands as it appeared in 1956 (left), 1958 (middle), and 1972 (right). The Port Authority development operation began in 1958 on 1,165 acres and has since

a controversial regional land use manager that works to balance public and private interests in the enormous Adirondack State Park. The park includes both publicly and privately owned land, including several small municipalities.

The agency reviews certain types of development proposals, including application for new subdivision. It imposes conditions for environmental protection when it grants permission to subdivide. The agency has won initial contests over an expansion of ecological conditions to include aesthetic judgments relating to wild countryside. For example, one recent set of conditions prohibited new boathouses along a stretch of rustic shoreline that was being subdivided. The subdivider's appeal was rejected in an initial court review, based in part on a careful examination of the New York Legislature's objectives in creating the agency.

In California, the San Francisco Bay Conservation and Development Commission also benefited greatly from a strong legislative statement in defense of the Bay in its authorizing legislation. Initial court challenges to tough dredge and fill regulations were rebuffed with references to the clear objectives the legislature had set out. The courts found that the power to regulate land uses in such sensitive areas "develops, within reason, to meet the changed and changing conditions (of the present day)."

Competing Public Interest

In estuarine areas, government agencies can sometimes claim a pre-existing public interest in coastal land to further justify strict regulation and sidestep constitutional challenge. The techniques and legal rules vary from state to state, but apply most frequently to sandy shores and tidal lands.

The Oregon State Legislature's declaration that the public had a right to use and enjoy the open beach was affirmed by the Oregon Supreme Court in 1969. The legislature had asserted a public right to use the open beach even though federal land grants ran to the line of mean high tide. The court examined the justification for the legislative action and found that it did not depend on public use of a particular path or area. That conclusion would have required detailed historical investigation of the pattern of use of each section of the beach. Instead, the court looked to the use of the coast as a whole, concluding that the ancient doctrine of custom justified the law. The regulation opening the state's beaches was uniquely suited to the situation. There had been virtually no development seaward of the vegetation line prior to the court challenge.

In California, similar rules have been applied on a narrower basis to define the circumstances that permit a public claim of access rights and recreational use. This legal doctrine of "implied dedication," or the use of a specific site without the permission of the owner for a period of years specified in state law, also sidesteps the constitutional issue. In California, it resulted in a rash of no trespassing signs and access fees. Access became a major factor in the statewide referendum in 1972 that created a coastal zone management program.

Even without the finding of "implied dedication" state and local regulations can require the dedication of public accessways in certain development situations, most frequently with the subdivision of land. The rationale is the same as that used when local governments require dedication of land for public streets in new housing developments. Court rulings on this issue vary from

been transformed into the major containerport of the United States, employing 3,190 people daily in 1975 with an annual payroll of $33.1 million. (Courtesy Port Authority of New York)

state-to-state but several states have a clear line defining what is and is not constitutional.

The legal rules surrounding the "public trust" in tidelands and adjoining shorelands provide the most confusing opportunities for legal scholars to sidestep the taking question. The doctrine has been infrequently examined in different state courts with inconsistent results. In the early nineteenth century, it was an established principle that title to tidal wetlands was reserved to the states with the creation of the federal union. In 1842, the United States Supreme Court reviewed the extent of these rights and agreed that earlier grants to private persons were subject to the public's rights held in trust by the state.

The notion has evolved differently in each of the coastal states. In general, the argument is that title remains in the state because the state holds title for the public trust. Grants for particular uses, such as wharfage and excavation, may be valid, but regardless of the nature of the grant, there is a residual public interest that may be asserted.

Unlike the legal principles surrounding dedication of property, the public trust remains a fuzzy subject area. Maryland's highest court approved legislation reasserting state title in "lands under the navigable waters of the state below the mean high tide, which are affected by the regular rise and fall of the tide." When riparian owners claimed a right to remove sand and gravel, their claim was disapproved because of the pre-existing state right defined in the statute.

The Maryland law uses the line of mean high tide to define the landward limit of the public trust. The result is a public right that cannot be destroyed merely by selling the land. The doctrine protects against shortsighted stewardship of the public resource. In most situations where private rights are granted in public trust land, the public trust may be reasserted after the passage of time or changes in statutes and conditions of use.

A more expansive view was adopted in Wisconsin, where the law includes fresh water wetlands in a public trust definition that is more closely tied to the natural water regime. In the *Just v. Marinette County* case, which was cited in the passage at the beginning of this article, the Wisconsin Supreme Court was asked to review a 1966 Shoreland Protection Act ordinance that had been adopted by the county. The Justs owned lakefront lots and began filling the shorefront swamp contrary to the ordinance that required a special permit for fill.

The public trust notion was linked to an explanation of the heavyweight character of the shoreland protection program. The court emphasized the special relationship between lands adjacent to and near navigable waters:

> *What makes this case different from most condemnation or policy power zoning cases is the interrelationship of the wetlands, the swamps and the natural environment of shorelands to the purity of the water and to such natural resources as navigation, fishing, and scenic beauty. Swamps and wetlands were once considered wasteland, undesirable, and not picturesque. But as the people became more sophisticated, an appreciation was acquired that swamps and wetlands serve a vital role in nature and are essential to the purity of the water in our lakes and streams. Swamps and wetlands are a necessary part of the ecological creation and now, even to the uninitiated, possess their own beauty in nature.*

The Court went on to cite cases supporting its conclusion that "the active public trust duty of the state of Wisconsin in respect to navigable waters requires the state not only to promote navigation but also to protect and preserve those waters for fishing recreation and scenic beauty."

Finally, navigability and navigation rights are closely related to public trust concepts in sidestepping constitutional problems, especially where bottom lands are in question. The power to control navigation is the principal authority behind federal permit requirements for bridges and construction in navigable waters. It is also important in state programs, particularly those that include navigability as part of the definition of the reach of the public trust.

Value

Value loss is an unreliable indicator of the constitutionality of a regulation, though it provides a quick reference to sources of controversy. Heavyweight nuisance abatement regulations often apply even when they result in actual cash losses or a high percentage reduction in land value. In other situations, the inability to pursue a modest improvement program may be sufficient to tip the balance with public purpose and invalidate a regulation. In coastal areas, the question is further complicated by the opportunities to sidestep the constitutional issue discussed earlier.

The Wisconsin Supreme Court offered a lesson on the tough implications of the interaction of these factors:

> *It seems to us that filling a swamp not otherwise commercially usable is not in and of itself an existing use, which is prevented, but rather is the preparation for some future use which is not indigenous to a swamp. Too much stress is laid on the right of an owner to change commercially valueless land when that change does damage to the rights of the public.*
>
> *The Justs argued their property has been depreciated in value. But this depreciation of value is not based on the use of the land in its natural state but on what the land would be worth if it could be filled and used for the location of a dwelling. While loss of value is to be considered in determining whether a restriction is a constructive taking, value based upon changing the character of the land at the expense of harm to public rights is not an essential factor or controlling.*

Other heavyweight situations relating to nuisance have been reviewed by the United States Supreme Court and they have made it clear that loss in value, even 80 percent or more, is not the sole criterion in marking constitutional limits on regulation. These situations—for example, closing a gravel pit—do not easily translate into the ecological perspective of estuarine management.

State courts have taken many tacks in facing the issue. A recent New Jersey discussion of wetlands management applied a "practical use" test: A permit program that allowed a number of use options if environmental standards were met did not "deny all practical use" and therefore did not overstep the constitutional limit.

The New Jersey decision seems to reflect the mainstream. Where there are strong declarations of public policy and a public agency cannot sidestep the constitutional question, relief is available, not for a particular degree of economic harm, but when no practical use for the property is allowed.

A successful court challenge usually results in the invalidation of the challenged regulation. Typically, a property owner will not collect money as a result. To provide a compensation alternative, some states have adopted laws requiring actual compensation. This process can lead to another legal quagmire, the catch-22 of the regulation/taking issue. Where the law requires compensation only if a regulation exceeds constitutional limits, it pushes all landowners into a "wipeout," or loss of development value, position, allowing compensation only in those cases of successful challenge. This occasional compensation is not the same sort of "windfall" bestowed by government when it builds a new bridge to an island, but it produces similar disparities in treatment of private landowners.

A valid regulation may result in substantial loss in value for a parcel of property. But valuation for compensation—in the event the regulation oversteps the constitutional limit (is invalid)—ignores the regulation and usually requires just compensation at the full market value. The results parallel the public refuge/regulated wetland analogy. Most property owners receive no compensation. Those who demonstrate the extreme circumstances that justify a court decision in their favor (and the costs of litigation) get full compensation. Often no middle ground remains to soften the effect of tough but valid regulations for those who must continue to live with them.

John Costonis, visiting professor at the University of California at Berkeley, began a dialogue on a judicial option for dealing with this problem in a recent article (*Columbia Law Journal*, January 1976), describing the "accommodation power." Crudely described, the power he advocates would permit partial compensation awards by the courts in the grey area between valid regulation and clear taking for public use. In another study, Don Hagman, a professor at the University of California at Los Angeles, also explores "windfalls for wipeouts" as another approach to the compensation issue. Unless a legislative or judicial solution of this sort emerges, controversy is likely to continue over the constitutional limits on regulation for estuarine management.

Conclusion

The constitutional arguments against estuarine management include a number of issues but center on often emotional arguments about private property and restrictions on its development. Long-standing controversies remain to be finally resolved before the courts in southwest Florida, Connecticut, and other states. Still, the possibilities for sidestepping the issue by both public agencies and private landowners make the likelihood of a clear resolution relatively small.

The essential elements of the argument are becoming more settled. There is growing agreement on the purposes of wetlands and flood plain management, two key elements of an estuarine management program. And the public's rights up to the mean high tide line (or its equivalent in a particular state) are well established in the absence of actions by the government or a landowner that create special rights.

Compensation remains an attractive alternative to regulation, but experience indicates that large amounts of money are needed to buy a small amount of land. And, in most cases where no public use is needed or intended, constitutional ambiguities, coupled with a legislature's ability to shift the issue to the courts, have combined to produce few opportunities for widespread access to relief except case-by-case before the courts. The courts, caught between the "all" of public acquisition and the "nothing" of valid regulation, have done little.

Aerial view of upper Newport Bay in Orange County, California, south of Los Angeles, showing both developed and undeveloped areas that have been subject to new state legislation on coastline construction. (Charles O'Rear/ Courtesy Environmental Protection Agency)

An operating hydraulic dredge pumping spoil to fill wetlands. When used to create building sites, this type of operation comes under strong legal attack based on federal and state laws. (The Conservation Foundation)

However, both the myth of unfettered use and the fear of uncompensated public use of private land are ill founded. Unless justified by a competing interest in private land, such as the public trust or navigation rights, public use requires "just compensation." But reasonable public regulation for a valid purpose—for example, wetlands or flood hazard management—does not fall under the same constitutional "taking" limitation.

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Correction

In the article "New York Bight I: Ocean Dumping Policies" by Richard T. Dewling and Peter W. Anderson in the Summer 1976 issue of *Oceanus,* the wrong conversion figure in square meters was given for the area of New York's Central Park. The sentence should have read: "For example, the amount of sewage sludge alone that was dumped in the Bight in 1974 would cover the 3,400,000 square meters [not 3400 square meters] to a height of 1.2 meters."

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